ABSTRACT

Title of Document: A MODEL-BASED HUMAN RELIABILITY ANALYSIS METHODOLOGY (PHOENIX METHOD)

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Despite the advances made so far in developing human reliability analysis (HRA) methods, many issues still exist. Most notable are; the lack of an explicit causal model that incorporates relevant psychological and cognitive theories in its core human performance model, inability to explicitly model interdependencies between human failure events (HFEs) and influencing factors on human performance, lack of consistency, traceability and reproducibility in HRA analysis. These issues amongst others have contributed to the variability in results seen in the application of different HRA methods and even in cases where the same method is applied by different analysts. In an attempt to address these issues, a framework for a model-based HRA methodology has been recently proposed which incorporates strong elements of current HRA good practices, leverages lessons learned from empirical studies and the best features of existing and emerging HRA methods. This research completely develops this methodology which is aimed at enabling a more credible, consistent, and accurate qualitative and quantitative HRA analysis. The complete qualitative analysis procedure (including a hierarchical performance influencing factor set) and a causal model using Bayesian Belief network (BBN) have been developed to explicitly model the influence and dependencies among HFEs and the different factors that influence human performance. This model has the flexibility to be modified for interfacing with existing methods like Standard-Plant-Analysis-Risk-HRA-method. Also, the quantitative analysis procedure has been developed, incorporating a methodology for a cause-based explicit treatment of dependencies among HFEs, which has not been adequately addressed by any other HRA method. As part of this research, information has been gathered from sources (including other HRA methods, NPP operating experience, expert estimates), analyzed and aggregated to provide estimates for the model parameters needed for quantification. While the specific instance of this HRA method is used in nuclear power plants, the methodology itself is generic and can be applied in other environments.

A MODEL-BASED HUMAN RELIABILITY ANALYSIS METHODOLOGY (PHOENIX METHOD)

By

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To the best husband - Joseph Ekanem, beautiful daughters - Aniekan and Idara Ekanem, greatest dad and mom - Imeyen and Nsemo Okonna, and beloved brothers - Idongesit and Ebukubong Okonna, THANK YOU!

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List of Acronyms

- AFW – Auxiliary Feed Water
- ASP – Accident Sequence precursor
- BBN - Bayesian Belief Network
- BP – Branch Point
- CCW – Component Cooling Water
- CFM - Crew Failure Mode
- CPC - Common Performance Condition
- CPT - Conditional Probability Table
- CREAM - Cognitive Reliability and Error Analysis Method
- CRT - Crew Response Tree
- CVC – Chemical Volume Control
- DBN – Dynamic Bayesian Network
- EOC - Error of Commission
- EOO - Error of Omission
- EOP – Emergency Operating Procedure
- ES - End State
- ET - Event Tree
- FCV – Flow Control Valve
- FT - Fault Tree
- GTT – Generic Task Type
- HEART – Human Error Assessment and Reduction Technique

- HEP - Human Error Probability
- HERA - Human Event Repository and Analysis
- HFE - Human Failure Event
- HSI - Human System Interface
- HRA - Human Reliability Analysis
- IDA - Information, Decision and Action
- IDAC - Information, Decision and Action in Crew Context
- IE – Initiating event
- IM – Intermediate Memory
- KB – Knowledge Base
- MFW – Main Feed Water
- MS – Mental State
- NARA – Nuclear Action Reliability Assessment
- NPP - Nuclear Power Plant
- NRC - Nuclear Regulatory Commission
- PIF - Performance Influencing Factors (same as PSF)
- PRA – Probabilistic Risk Assessment
- PSF - Performance Shaping Factor (same as PIF)
- RCP - Reactor Coolant Pump
- RCS – Reactor Cooling System
- SACADA - Scenario Authoring, Characterization, and Debriefing Application
- SDP – Significant Determination Process
- SG – Steam Generator

- SHSC – Secondary Heat Sink Control
- SI – Safety Injection
- SPAR-H - Standard Plant Analysis Risk HRA method
- THERP - Technique for Human Error Rate Prediction
- TOE – Training Objective Element
- UAT – Unit Auxiliary Transformer
- WM – Working Memory

1 Introduction

1.1 Motivation

Humans are present in every aspect of a system and are responsible for its design, manufacture, safe operation and maintenance. Hence, their contribution to risk cannot be overstated as it is typically in the range of 60% - 90% [1], [2]. This high percentage of accidents and incidents involving human error in recent years has emphasized the need to study human performance in order to more accurately predict and quantify human error. The termination of Three Mile Island (near Harrisburg, PA) nuclear power plant's (NPP) safety injection system by plant crew which led to the extensive damage sustained by the reactor core (03/1979) [3], the fatal runway overrun accident caused by the pilot and air controller of Comair Flight 191 in Lexington, KY (08/2006) [4], the fatal crash of the cruise vessel "Costa Concordia" off the Tuscan island of Giglio, Italy due to the Ship master's error (01/2012) [5] are a few of the many examples of accidents caused by human error.

The means by which human contribution to risk is assessed both qualitatively and quantitatively is known as Human reliability analysis (HRA), which is an important component of an integrated probabilistic risk assessment (PRA). As a discipline, HRA aims to identify, model and quantify human failure events (HFE) in the context of an accident scenario. Presently, dozens of HRA methods that can be used exist and new methods are still being developed. Despite all advances made so far in developing these HRA methods, many issues still exist. Most notable are; the lack of a causal model that formally incorporates relevant psychological and cognitive theories in its core human performance model, inability to explicitly model interdependencies between influencing factors on human performance and human failure events, lack of consistency, traceability and reproducibility in the qualitative and quantitative HRA analysis. These issues have led to variability in the results seen in the applications of the different HRA methods and also in cases where the same method is applied by different HRA analysts.

In an attempt to address the aforementioned difficulties, a framework for a model-based HRA methodology has been proposed that incorporates strong elements of current HRA good practices and leverages lessons learned from empirical studies and the best features of both existing and emerging HRA methods. It formally incorporates relevant cognitive and psychological theories in its human performance model on which the qualitative analysis tools and procedures of this method are built. This framework has two coupled phases of analysis which are the qualitative and quantitative analysis. It is intended to support HRA in full-power internal events PRAs, low-power shutdown (LPSD) operations, event assessment and significant determination processes (SDPs), fire and seismic PRAs [6].

While this specific instance of the methodology is used in Nuclear Power Plants (NPP), the methodology itself is generic and can be applied across different industries and environments including oil & gas, aviation, power generation etc.

1.2 Research Objectives

In order to accomplish the intent of the proposed framework, the goal of this research is to fully develop both the qualitative and quantitative analysis phases of the Model-Based HRA methodology and demonstrate its capabilities.

The development of the qualitative analysis methodology is achieved by:

- Enhancing the crew response tree (CRT) construction process for consistency and completeness by improving the overall structure of the flowchart used for CRT construction and also incorporated timing of crew responses.
- Enhancing the framework to include more error modes (referred to as crew failure modes (CFMs)) in order to capture the various modes in which NPP operating crews could fail while conducting their day-to-day activities.
- Enhancing the human response model (IDA) which is represented by fault trees, for more accurate identification of human failure events (HFEs) and scenarios leading up to the HFEs.
- Providing guidelines for conducting task analysis and catalog of information required by the analyst in support of the HRA analysis process.
- Developing of a comprehensive set of performance influencing factor (PIF) groups and hierarchy which enables information to be captured at different levels of detail.
- Developing of a framework for relating CFMs to PIFs based on possible causes of failure and mechanisms for human error. This framework provides a means for developing a structured, causal model for the quantification approaches in this research work.
- Developing a BBN causal model based on the CFM-PIF framework to model the effects of the influence of PIFs on crew performance. The BBN model nodes are made up of CFMs and PIFs, and the relationships between the nodes are based on the links in the CFM-PIF framework. This model has the flexibility to be

modified for interfacing with existing HRA methods like SPAR-H. Note that this is of particular interest to HRA practitioners since SPAR-H is widely used in USA nuclear power plants for HRA.

The development of the quantification framework and methodology for HEP estimation is based on the BBN model. This is achieved through:

- The development of a methodology for the BBN model quantification.
- The development of a methodology for HFE dependency modeling and quantification by incorporating the time slice concept of Dynamic Bayesian Networks (BBN) into BBN modeling and quantification.
- The development of a methodology for assessing the levels of the different PIF states for input into the BBN model. These PIF levels are a part of the model parameters required for HEP estimation.
- BBN Model parameter estimation by the use of Bayesian methods to incorporate data from sources which included other HRA methods, NPP operating experience, and expert estimates, through a detailed data gathering and analysis process.

Example applications are used to demonstrate the capabilities of the methodology through step-by-step implementation. The examples include applications such as accident sequence precursor analysis (ASP), event assessment, and significant determination process (SDP).

1.3 Overview of Dissertation

Following this introductory chapter (which provides a general overview of this dissertation and its contributions), chapter 2 provides an introduction to current HRA practices and the challenges in the industry which led to the recently proposed model-based framework. It also gives an overview of the framework and the human response model (IDA) adopted for this methodology. Chapter 3 gives a high level overview of this research in terms of the contents of the subsequent chapters of this work.

Chapter 4 provides an overview of the qualitative analysis process, including guidelines for task analysis. Chapter 5 through 10 discusses the different elements of the qualitative framework. It includes; the crew response trees (CRTs) and the construction flowcharts in chapter 5, Human response model fault trees in chapter 6, Crew failure modes (CFMs) in chapter 7, proposed PIF groups and hierarchy in chapter 8, CFM – PIF framework development in chapter 9, and the BBN model development in chapter 10.

Chapter 11 provides an overview of the quantitative analysis process. Chapter 12 through 14 discusses the different aspects of the quantitative analysis framework It includes; BBN model quantification in chapter 12, HFE dependency modeling and quantification in chapter 13, and data sources and parameter estimation in chapter 14.

Chapter 15 demonstrates the application of this methodology to support different types of operations in NPP including ASP, event assessment, base line model, and SDP. The summary and conclusions (which include contributions of this research, challenges and the possible future directions) of this work are discussed in chapter 16.

A series of appendices provide additional details and supporting data used in the proposed methodology.

2 Related Work

2.1 HRA Overview

As previously stated, the means by which human contribution to risk is assessed both qualitatively and quantitatively is known as Human Reliability Analysis (HRA). HRA aims to identify, model and quantify human failure events (HFE) in the context of an accident scenario. It is also an important component of an integrated probabilistic risk assessment (PRA) for complex systems such as nuclear power plants. As a discipline, it is used to understand and assess the effect of human on system risk, thereby incorporating this into PRA with the overall goal of reducing the likelihood and consequences of errors made by humans.

Presently, dozens of HRA methods exist and new methods are still being developed everyday. In the nuclear industry, the need for improved HRA methodologies for application to PRAs has motivated a number of major activities in research and development worldwide since early 1990s. These efforts have resulted in some improvements in the application of the so-called first generation HRA methods, and a number of new techniques and frameworks often referred to as second generation, or advanced methods have been developed. In comparison to the first generation methods, and with respect to the number and scope of applications, the second-generation methods are still mostly in the development phase or trial applications.

2.1.1 First-Generation HRA Methods

These methods typically have a set of error modes defined, most of which are commonly assumed to be Errors of Omission (EOO). Human error probabilities (HEPs) are generally calculated without specifically identifying the error modes. Typically, task analysis is conducted, nominal error rates are assigned and PIFs are utilized to adjust the error rates. Some methods provide a list of PIFs while others let the analyst specify the relevant PIFs for the HEP estimation. For example, THERP (Technique for Human Error Rate Prediction) [7] provides rules for performing predictive task analysis; however, no specific guidance is given for error mode identification. It assigns nominal error rates which are based on the characteristic of the activities derived from qualitative task analysis. It provides a PIF list but only three PIFs from the list are used in HEP calculations. It also does not provide specific guidance for cause identification. Its level of task analysis is more closely associated with the types of operator actions rather than the underlying cognitive processes driving operator behavior.

2.1.2 Second-Generation HRA Methods

Over the past two decades the development of new HRA methods has taken place mostly along two parallel tracks. One track attempts to enhance the quality of HRA analysis within the “classical” framework of PRA [8], [9], [10]. The other track reflects the belief that substantive improvement in HRA for PRA applications requires structural changes to the PRA methodology, moving from the static, hardware-driven view of the world to a more flexible dynamic model of accident scenarios. One way of achieving this is by integrating models of operator behavior, plant thermal-hydraulic response, and systems performance in a probabilistic-deterministic simulation approach [11]. Of course these two tracks also share many common objectives and face many similar challenges. Both intend to address error identification and probability estimation which are the two key components of a comprehensive HRA methodology.

With regards to the first track, these methods typically consider the context influencing the operator's cognitive decisions and the emphasis is on identifying Error of Commission (EOC). In general, separate error modes are assigned to different HEPs. For example, CREAM (Cognitive Reliability and Error Analysis Method) [12] identifies error modes for different cognitive activities (e.g. monitoring, diagnosis) and human functions (e.g. observation, execution). Thereafter, error rates are determined based on the cognitive activities and human functions with PIFs being utilized to adjust the error rate. Hence, second-generation methods have an increased emphasis on context and operator cognition than first-generation methods. However, these methods still have some limitations which include:

- The lack of sufficient theoretical and experimental basis for the key ingredients and fundamental assumptions of many of these methods.
- The lack of a causal model of the underlying causal mechanisms to link operator response to measurable PIFs or other characterization of the context.
- Majority of the proposed approaches still rely on very simple and in some cases implicit functions to relate PIFs to probabilities without the theoretical or empirical basis for such relations.

- In many instances, numbers are the result of expert elicitation, use of highly subjective scales, and unsubstantiated “reference probabilities”.

2.2 Current Problems in HRA

The results and insights from PRAs are frequently used to drive risk informed decision making processes. Since HRA is a significant component of PRA, it is important to obtain consistent HRA results for inclusion in PRAs. A notably issue in the HRA discipline is the variability of results seen in the application of different HRA methods and also in cases where the same method is applied by different HRA analysts. Evidence has been indicated by HRA empirical studies [13], [14], [15] that for a particular HFE, the HEP can significantly vary depending on the HRA method being applied and the analyst conducting the assessment. This variability can be traceable to some underlying issues including; the lack of a causal model that formally incorporates relevant psychological and cognitive theories in its core human performance model, inability to explicitly model interdependencies between influencing factors on human performance and human failure events, lack of consistency, traceability and reproducibility in the qualitative and quantitative HRA analysis.

Hence the US Nuclear Regulatory Commission (NRC), in an attempt to address these issues developed a uniform set of good practices [16] that should be considered when performing and reviewing HRAs. The HRA good practices are of a generic nature meaning that they are not tied to any specific HRA method. It provides a reference guide to the processes, individual tasks, and decisions that would be expected to take place in an HRA so that the results can sufficiently represent the anticipated human operator performance for inclusion in PRAs. As part of this effort, a set of desired attributes of a robust HRA method was identified during a workshop organized by the US NRC and attended by HRA experts. The attributes include [17]:

- Validity of the contents (plant, crew, cognition, action, EOCs, EOOs) etc.
- Better causal models for relating error mechanisms to context and theoretical foundations.
- Clear definition of the "unit of analysis" and level of detail required for various applications.
- Adequate coverage of HFE dependency and recovery.
- Reliability (reproducibly, consistency).
- Capability for Graded Analysis like screening, scoping, detailed analysis.
- Empirical Validity of HEPs like having basis in Operational Data, Simulator Experiments, etc.
- Traceability/Transparency i.e. ability to reverse engineer the analysis.
- Ability to test the entire or part of the model and analysis.
- Usability/Practicality.

The US NRC also led an effort to evaluate some HRA methods that are commonly used in regulatory applications against the formulated good practices [18]. As part of this effort, the strengths and limitations regarding the underlying knowledge and databases were also evaluated. These evaluations were done by eliciting input from recognized HRA experts representing the NRC, different industries, organizations and the private sector. The methods reviewed included some of the first and second generation methods including THERP [7], SPAR-H [19], etc. The results obtained from this evaluation and the uniform set of good practices formed the basis for determining the features needed in an HRA method and suggested the development of a hybrid approach capturing most of the positive features of the existing HRA methods. This led to the development of the framework for a model-based hybrid HRA methodology.

2.3 Desirable characteristics of an advanced HRA method

In general, below is a high-level list of some desirable characteristics of an HRA method [8]:

- Identification of human response (errors are the main focus) in PRA context.
- Estimation of response probabilities.
- Identification of causes of errors to support the development of preventive or mitigating measures.
- Inclusion of a systematic procedure to aid in the generation of reproducible qualitative and quantitative results
- Inclusion of a causal model of human response with roots in cognitive and behavioral sciences, and with elements (e.g., PIFs) that are directly or indirectly measurable, and a structure that provides unambiguous and traceable links between its inputs and outputs.
- Detailed enough to support data collection and empirical validation at elemental levels. In general, data and models are tightly coupled. The model should be data-informed, and conversely data collection and analysis must be model-informed. A coordinated model-based collection and analysis of experimental and field data

should support the development and application of the model, and quantification of its parameters.

Reason [20] distinguishes three levels of human error classification: behavioral-level, contextual level, and conceptual level, addressing the "what", "where", and "how" of human errors. The conceptual-level error classification needs a cognitive model to trace errors to their origins, at levels below the overt errors. This classification and other similar ones provide a useful reference point for evaluating the depth of the HRA methodologies. Most of the first and even some of the recent second generation HRA approaches, stay at the behavioral and contextual levels. These levels, however, are not sufficient to meet some of the key expectations for an advanced HRA approach. It can be argued that:

- Only a causal model can truly provide both the explanatory (conceptual level) and predictive capabilities. Without a causal model, it is difficult for instance to explain why in some cases seemingly similar contexts result in different operator responses.
- Only a model-based approach provides the proper framework for tapping into and integrating models with data from the diverse scientific disciplines that cover different mechanisms and aspects of human behavior. Without a causal model it is difficult to understand the relationship between PIFs and human behaviors, and their application in HRA.
- A causal model that explicitly captures the generic and more fundamental aspects of human response can be tested and enhanced using data and observations from diverse contexts and application domains. This is particularly important as the

situations of interest in HRA are highly context-dependent and rare, meaning that adequate statistical data are unlikely to be available for a direct estimation of operator response probabilities.

- A generic causal model will have a much broader domain of applicability, reducing the need for developing application-specific methods. For instance, the same underlying model can be used for errors during routine maintenance work as well as operator response to accidents.
- A model-based HRA method can significantly improve reproducibility of the results and robustness of the predictions.
- Only a model-based approach provides a vehicle for orderly improvement of models and data, by identifying the data gaps and highlighting weak links, and questionable assumptions.

It is evident that building a causal model of human behavior for HRA applications is an extremely challenging undertaking. Expectations from such a model should be set considering current state of the art in the supporting disciplines, and practical constraints in data collection and empirical observations. Some critical aspects of human cognitive behavior are currently at best only research subjects. Reliable scientific models are likely to emerge in the future at the cross-section of such fields as psychology, behavioral sciences, ergonomics, and neuroscience. Nevertheless, even with what we currently know from these disciplines, augmented with insights and data from actual operating experience, significant steps can be taken beyond what the current HRA methods could offer.

2.4 The Model-Based Hybrid HRA Methodology

The model-based hybrid HRA methodology was developed in an attempt to incorporate strong elements of current HRA good practices [16] and to leverage lessons learned from HRA empirical studies [13] [15] with the best features of both existing and emerging HRA methods. It formally incorporates relevant cognitive and psychological theories in its human performance model on which the qualitative analysis tools and procedures are built. This framework has two coupled phases of analysis which are the qualitative and quantitative analysis and it is intended to support HRA in full-power internal events PRAs, low-power shutdown (LPSD) operations, event assessment and significant determinations, fire and seismic PRAs [6]. Note that crew as a whole is the unit of analysis in this methodology and not the individual operator.

The qualitative analysis part of the methodology introduces the "crew response tree" (CRT) which provides a structure for capturing the context associated with the HFE, including EOO and EOC. It also uses a team-centered version of the Information, Decision and Action (IDA) model [22] and "macro cognitive" abstractions of crew behavior as well as other relevant findings from cognitive psychology literature and operating experience, to identify potential causes of failures and influencing factors during procedure-driven and knowledge-supported crew-plant interactions. The result of this analysis is the set of identified HFEs and the likely scenarios leading to each. The qualitative analysis approach is intended to be generic in the sense that it should be compatible with various quantification methods.

The quantification framework uses a conditional probability expression, associating the conditional probability of an HFE with probabilities of the contexts as given by PRA scenario, human failure mechanisms, and the underlying “performance influencing factors”. Such mathematical formulation can be used to directly estimate HEPs using various information sources (e.g., expert estimations, anchor values, simulator or historical data), or can be modified to interface with existing quantification approaches.

As part of the development of this methodology, the focus has been to provide guidance and assistance for HRA analysts with a wide range of skill levels. This is due to the growth in risk-informed applications which has demanded the use of HRA methods in generating inputs to risk-informed decision-making processes by analysts who are not experts in cognitive science. The development also envisions software-supported quantitative analysis, to build and analyze CRTs, identify Crew Failure Modes (CFMs), develop the human failure scenarios, and to support a number of quantification options.

2.4.1 The Qualitative analysis framework

The broad objective of HRA qualitative analysis is to identify HFEs and characterize crew-plant scenarios that lead to those HFEs. As such, there is a tight coupling between understanding and analyzing the plant/system response and conditions (systems behavior), and understanding and analyzing the crew activities (operator behavior). Therefore, the process of HFE identification and defining the scenarios leading to the HFEs is, in general, inseparable from the process of modeling the plant response in a PRA.

PRAs use event trees (ET) that define logical (and often temporal) sequences of binary events starting from an initiating event and resulting in plant End States (ES). Major functional responses of the plant and key crew actions constitute the various elements (top events) of the ET. The sequences of ET are typically the high level PRA scenarios (S). The details of how the plant functions fail as a result of failure of component or human actions are typically included in fault trees (FT) attached to various events of the ET. The combinations of the events in these FTs, which are logically linked according to the ET scenarios, form the more detailed picture of the PRA scenarios (scenario cut-sets). Such sets are defined in this qualitative methodology as the PRA scenario context (S).

The proposed qualitative analysis framework uses two modeling vehicles namely [6]: (1) A process and representational method for analyzing crew-plant interactions with a focus on the identification and quantification of HFEs and possible recoveries, and (2) A human response model which relates the observable crew failures modes (CFM) to "context factors" for example, PIFs.

2.4.1.1 Layers of the qualitative analysis framework

The qualitative analysis process has three main layers namely:

- The CRT (top layer)
- The human performance model (mid layer)
- The PIFs (bottom layer)

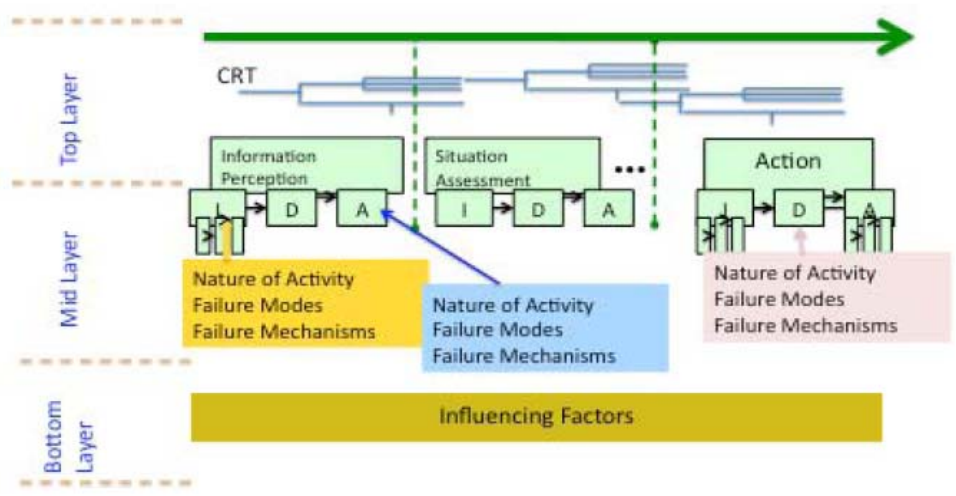


Figure 2-1: The three layers of the qualitative analysis framework [23]

2.4.1.1.1 The CRT (Top layer)

Mosleh et al. [6] states that the crew response tree (CRT) which is a forward-branching tree of crew cognitive activities and actions is the first modeling tool for the qualitative analysis process. It is a crew-centric visual representation of the crew-plant scenarios which provides the roadmap and blueprint that supports the performance and documentation of the qualitative analysis. It serves as an aid to the analyst and is also envisioned as an HRA work product, i.e. a means of documenting and reporting the qualitative analysis. Its role is to ensure a systematic coverage of the interactions between the crew and the plant that is consistent with the scope of the analysis being conducted, thereby providing traceability for the analysis.

The assumption made is that the customary steps of building a PRA model which starts with development of ETs for various initiating events, have been taken for many of the applications of the proposed methodology. In some PRAs, the process starts with developing a set of event sequence diagrams (ESD) and thereafter, ETs which are based on the ESDs. In order to assist in making the development of the CRT consistent with the PRA scenarios being considered, either the ET or ESD can be utilized.

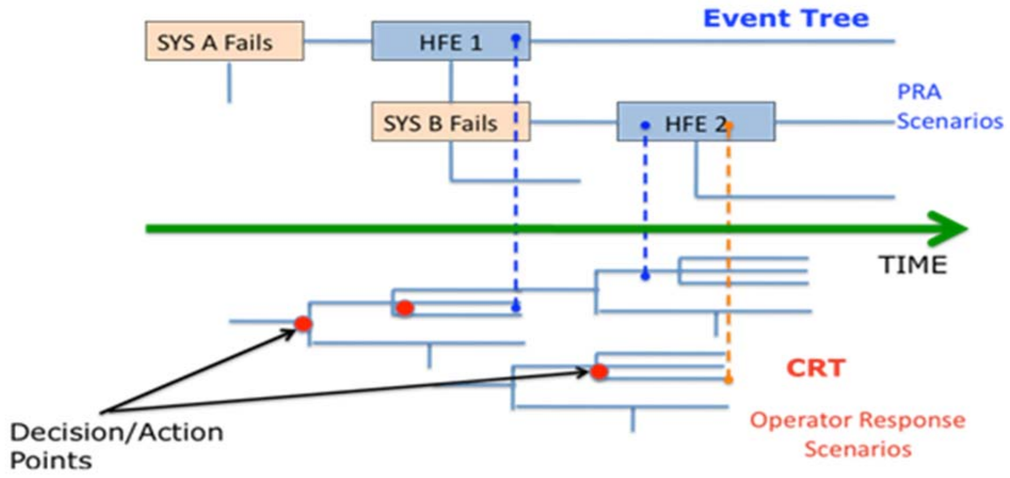


Figure 2-2: Modeling Plant and Crew Interaction through CRT [6]

Figure 2-2 indicates the conceptual relation between CRT and a typical PRA ET. The plant ET for an initiating event with system failures and HFEs is shown above the time arrow. The CRT which serves as a supporting tree is shown below the time arrow. Both the ET and CRT are synchronized and this is symbolized by the green arrow. The CRT gives the causal explanation of the HFEs. Symbolically, the causal explanations (links) are shown as dashed lines. The purpose of the link is to aid the analysts in keeping track of the relation between the CRT scenarios and event tree scenarios; it is not a formal mathematical or logical link. The nodes or branch points of the CRT can include operator decisions and actions, relevant plant/system functional states, as well as crew interactions (if the unit of analysis is each individual operator rather than the crew). In the CRT, each sequence of events indicates a graphical representation of one of the possible crew response across the entire accident sequence. This would aid in increasing consistency and reducing variability in the HRA task analysis. The ET and corresponding CRT start at the initiating event (for full power applications). Looking at this conceptual picture, the possibility of having multiple CRT scenarios leading to the same HFE as defined in the PRA model (note the two dashed lines pointing to two CRT scenarios for HFE2.) is observed. Also, a given CRT scenario may include multiple HFEs. Therefore, it can be used to find the paths to predefined HFEs and possible recoveries, or used as an aid to identify new HFEs.

2.4.1.1.2 Human performance Model (Mid-layer)

The CRT branches are defined mainly at the functional level and typically do not cover the underlying human failure mechanisms and their causes. Hence, its structure captures some but not all aspects of crew responses and contextual factors. The remaining aspects of the context are captured by a set of supporting models of crew behaviors in the form of causal trees that are linked to the CRT branches.

The encompassing human response model adopted to serve as the basis for this linkage is the crew centered version of the Information, Decision and Action (IDA) cognitive model [21], [22] which was originally developed to model nuclear power plant operator response in emergency situations. Given the incoming information in IDA, a response is generated by the crew model which links the context to the action through explicit causal models. IDA is a three stage model and these stages serve as the basis for linking failure mechanisms to the possible human failures. This model adapts well to the information processing models commonly used in the human factors and cognitive psychology disciplines. The IDA stages are as follows:

- Information (I) stage: This stage is focused on the perception of the crew's environment and the cues they are presented with. Cognitive processing of information by the crew is limited to the task of information perception and prioritization.
- Situation Assessment/Decision stage: The crew in this phase uses the perceived information and the cues presented to them in the (I) stage, along with stored memories, knowledge and experience to understand and develop a mental model of the situation. Following the situation assessment, the crew engages in decision-making strategies to plan the appropriate course of action. External resources such as procedures may be used by the crew to assist in both the situation assessment and decision-making parts of this stage.
- Action (A) stage: This is the final IDA stage where the crew executes the chosen course of action.

A nested IDA structure may exist within each IDA element [11]. This implies that each phase of the I-D-A structure may be decomposed into sub I-D-A structures as needed for task analysis and for parsing of different human activities into sub-tasks or sub-events. For example I-in-I involves information being perceived and recognized, D-in-I involves the decision on what to do with the perceived information and A-in-I involves any actions taken as result of the decision made (mainly gathering of new information) .

CFMs are used to further specify the possible forms of failure in each IDA phase. CFMs are generic functional modes of failure of the crew while interacting with the plant. They cover different modalities in crew response, including procedure driven, (PD), knowledge driven (KD), or a hybrid of both (HD). They can be mapped to physiological and psychological causes and their contextual factors or reasons. CFMs are tailored to the various sub-tasks that can be identified for the procedure driven crew interactions in nuclear power plants in the PD mode.

2.4.1.1.3 Performance Influencing Factors (PIFs) – Third layer)

PIFs form the third layer of the qualitative analysis framework. PIFs also referred to as performance shaping factors (PSFs) are context factors (including plant factors) that affect human performance and can either reduce or increase the likelihood of error. These PIFs are contextual factors that are not captured in the first two layers of the qualitative analysis.

2.4.2 The Quantification framework

An HFE is the result of one or several sequences of events or conditions (overall context) for a given plant PRA scenario (S). According to the CRT and corresponding linked causal models, the estimation of the human error probability (HEP) consistent with a “scenario-based” approach is done as follows [6]:

$$p(HFE \mid S) = \sum_{i=1}^{I} p(HFE \mid FM_i) \left[\sum_{j}^{J} \mathrm{p}\,(FM_i \mid \mathrm{F}_{j1}, \mathrm{F}_{j2}, \ldots\ldots, \mathrm{F}_{jn}; \mathrm{S}) \times p(\mathrm{F}_{j1}, \mathrm{F}_{j2}, \ldots\ldots, \mathrm{F}_{jn} \mid S) \right] \tag{2-1}$$

- “The summation in the brackets indicates the probability of i-th failure mode (FM) meaning CFM considering all possible CRT scenarios (j = 1, 2, …, J) that lead to the HFE of concern. Each scenario is characterized by a set of n factors (or different instances of a fixed super set of factors). The set {Fj1, Fj2, …, S} includes the usual PIFs and everything else in the scenario context that affect the probability of HFE.

- The term p(FMi | Fi1, Fi2, …) is the probability of i-th CFM for a given CRT scenario, and p(Fi1, Fi2 , …| S) is the probability of that scenario in the context of the PRA scenario S.
- One can define CFMs in such a way that P (HFE | FMi) =1 for all "i". In this case the aim of the HRA quantification model is to assess the values of p (FMi | Fj1, Fj2, …) and p(Fj1, Fj2, …| S) for each sub-context j."

In theory, all PIFs need to be considered in estimating p(FMi | Fj1, Fj2, …) and p(Fj1, Fj2, …| S) for each CRT scenario j and FMi. However, the crew response modeling methodology provides a basis for down-selecting those PIFs that are most relevant to each CFM. The formulation above symbolically indicates that in quantifying p(FMi | Fj1, Fj2 , …) and p(Fj1, Fj2, …| S) one should take into account the collective effect of the set of relevant PIFs for each CFM. Contrary to the assumption made in many popular HRA methods, a consensus is emerging indicating that PIFs are in fact interdependent. Such interdependencies should be explicitly acknowledged in quantification of p(FMi | Fj1, Fj2, …) and p(Fj1, Fj2, …| S). This provides the motivation to use influence diagrams (BBN) to, as a minimum, capture in a qualitative way the PIF interdependencies. The core of this research is the development of this quantitative analysis framework.

2.5 Overview of IDAC

IDAC (Information, Decision and Action in Crew Context) is an operator behavior model developed based on many relevant findings from cognitive psychology, behavioral sciences, neuroscience, human factors, field observations, and various first and second-generation HRA methodologies [11]. It models individual operator's behavior in a crew context and in response to plant abnormal conditions. Three generic types of operators are modeled: Decision Maker (e.g., Shift Supervisor), Action Taker (operators at the control panel), and Consultant (e.g., resource experts in the control room). IDAC models constrained behavior, largely regulated through training, procedures, standardized work processed, and professional discipline. These constraints significantly reduce the complexity of the problem, when compared to modeling general human response. IDAC covers the operator's various dynamic response phases, including situation assessment, diagnosis, and recovery actions.

At a high level of abstraction, IDAC is composed of models of information processing (I), problem solving and decision-making (D), action execution (A), of a crew (C). Given incoming information, the crew model generates a probabilistic response, linking the context to the action through explicit causal chains. Figure 2-3 is a schematic representation of the main elements of the IDAC modeling concept and its key elements in form of the umbrella I-D-A dynamic loop for each member of the crew.

IDAC is composed of (1) a Problem Solving Model, (2) Mental State and Engine of Cognition, (3) Memory and Knowledge Base Model, (4) Casual Model of Internal and External Performance Shaping Factors. Cognitive engine of IDAC combines the effects of rational and emotional dimensions to form a small number of generic rules of behavior that govern the dynamic response of the operator.

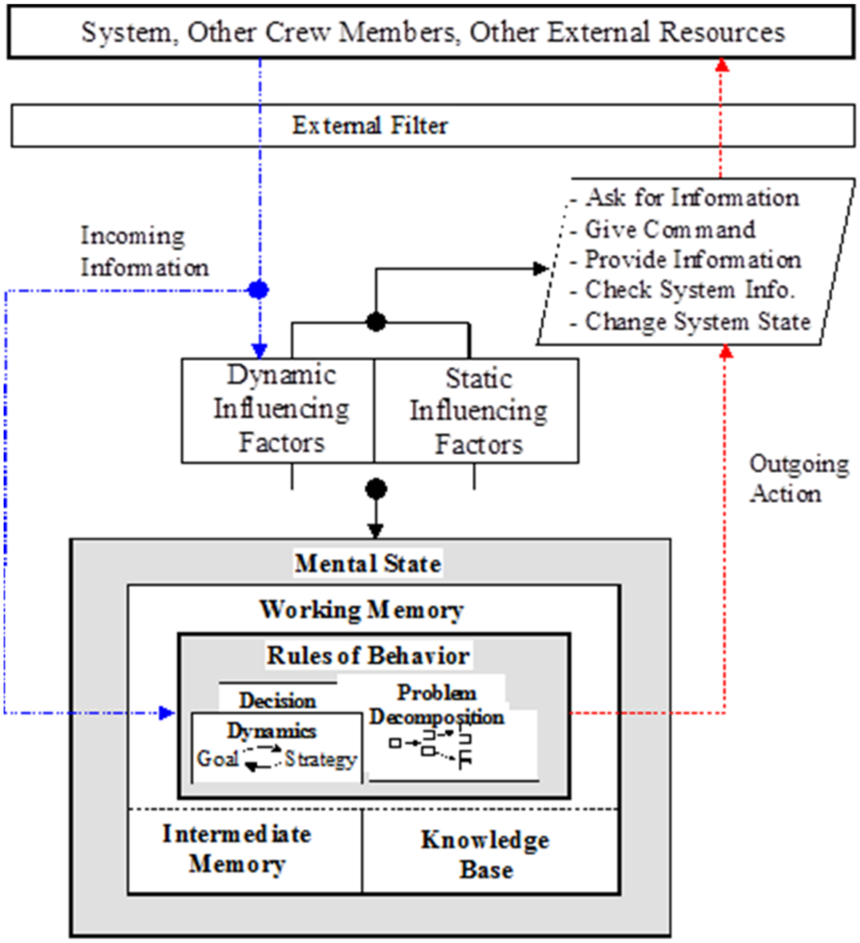


Figure 2-3: High Level View of the IDAC Dynamic Response Model

2.5.1 Architecture of IDAC

The architecture of IDAC is such that its main modeling elements can be repeatedly embedded in a layered and progressively detailed representation of the cognitive process. The various elements of the IDAC architecture are briefly described in the following sections.

2.5.1.1 Information Processing and Memory Model

The information-processing model (I) covers the perception, comparison, abstraction and grouping, of incoming information, as well as retrieval and distribution of the information among various types of memory. It filters the incoming information based on the human information procession capability (e.g., the 7±2) and considers information importance and similarity (e.g., source similarity) in the process. IDAC model includes three types of memory: working memory (WM), intermediate memory (IM), and knowledge base (KB). WM stores limited information related to the current cognitive process. IM, theoretically unlimited in capacity, stores information related to recent cognitive processes, which could be easily retrieved at any time given appropriate stimuli. KB, also theoretically unlimited in capacity, stores all problem-solving related knowledge obtained from training and experience. IDAC through its "cognitive engine" regulates the information relocation via among the various memory memories with explicit rules.

2.5.1.2 The Problem Solving Model

Any cognitive response of the operator to a situation, which has been brought to the operator's attention through the information perceived, is translated into a problem statement or goal, requiring resolution. The process of problem solving or goal resolution involves selection of a problem solving method or strategy. For nuclear power plant operation, examples of high-level goals include "normal operation", "trouble shooting", and "maintain plant safety margin".

Problem solving strategies cover a wide spectrum from simple direct association of the problem to a ready-made solution, "direct matching", to more complex systematic search/selection of a solution among possible candidates, “knowledge-based reasoning”. The list of strategies of course includes the most likely strategy of “procedure following”, but also “wait and monitor” and “trial and error”. There are also hybrid strategies mixing, for example, Knowledge-Based Reasoning and Procedure Following to form a more human-like hybrid problem solving strategy of “selective procedure following”. There is a hierarchy of goals and sub-goals, such that complex problems are broken down into simpler ones, and solved one at a time or concurrently, using corresponding strategies.

The problem solving process involves a series of decisions to be made or solutions to be selected based on available alternatives. The decisions making stage has its own strategy: “cost-benefit optimization”. Together, the problem-solving and decision-making processes constitute the second major structural part (D) of the IDAC model. This element covers the operator response phases of “situation assessment” or “diagnosis” as well as “response planning”. The action taking process (A) executes the decision made through the D process.

2.5.1.3 Mental State and Engine of Cognition

Human response is a dynamic process, guided by certain cognitive and behavioral rules, and influenced by physical and psychological factors. Memory, knowledge, and emotions, together with the core cognitive and intellectual faculties, are at work. A simple representation of the process steps and elements in terms of a hierarchy of goals and problem solving strategies is clearly an insufficient model for predicting or describing the behavior. The model also needs to cover, for instance, why and how a response process initiates, why and how a cognitive activity starts and continues, and why and how a goal or strategy is selected or abandoned. The process needs a motive power or internal engine to run, i.e., to go through the I-D-A process dynamically and in response to changing external and internal environments. IDAC's model of this engine is comprised of the Mental State with its set of elements (state variables), a set of rules of behavior, and information processing engine of WM.

Cognitive engine of IDAC combines the effects of rational and emotional dimensions (within the limited scope of modeling the behavior of operators in a constrained environment) forming a small number of generic rules of behavior that govern the dynamic response of the operator. The Mental State registers psychological dimensions or the stream of feelings associated with the external factors, in form of stimuli and possible tendencies to act on the stimuli. The stimuli are an individual's perception and appraisal of the external world (e.g., perception of criticality of system state, perception of problem solving recourse, and perception of task complexity). The tendencies to act on the stimuli include the individual's internal feelings pertaining to the stimuli (e.g., time constraint, task load, and information load). These then result in various psychological and cognitive moods (e.g., stressed, alert, attentive to task and surrounding environment), which could affect an individual's many kinds of judgments and behaviors. Another group of Mental State elements in IDAC include the individual's personal characteristics such as self-confidence, and attitude.

The psychological states are influenced by factors external to the individual, and include the team-related factors (e.g., coordination, cohesiveness, communication quality), organizational factors (e.g., work process design, tasking, procedure quality, tool availability) and external factors (e.g., physical access, environmental factors, man-machine interface, and other conditioning events such as hardware failures).

A significant number of studies were reviewed to identify possible candidates for the factors in IDAC. A key requirement in developing a list of factors for use in a causal model is to have a precise definition of each factor, and to ensure they that they do not overlap in their definition and role in the model. This is extremely difficult given the current state of the art, the quality, form, availability of relevant information, and complexities of communication across diverse disciplines that study the subject often for entirely different reasons and end objectives. IDAC has made an attempt to meet these requirements. One example is the way two Mental State elements of Time-Constraint Load (TLC), and Task-Related Load (TRC).

IDAC uses an influence diagram to represent a set of cause-effect relations and interdependencies among these variables (factors), and between these variables and the incoming information perceived by the operator. This influence diagram is supplemented by a set of mathematical relations for more explicit set of relationships, which often take the form of a metric for tendencies and/or stochastic relations, rather than deterministic links. The assumed forms of these relations reflect the model developers reading of the available empirical and theoretical models, event analysis, simulator exercises, as well as the opinions of other searchers and practitioners expressed in the HRA literature. No formal validation has been performed.

2.5.2 Modeling of the Dynamics of the Process

The cognitive engine (its parameters, factors, and rules) operates on the memory, and generates the cognitive behavior in response to the situation or context within which the cognitive activities have been initiated. Clearly this is a dynamic process, and the set of Mental State parameters and variables, as well as the content of the various memories (including the knowledge base) are continuously updated during the course of the operator-system interactions. Dynamic nature of operator response is due in part to the change in some of the external factors (e.g., incoming information about the new state of the systems). The external factors are, therefore, divided into two groups of dynamic and static, where the distinction is based on whether the state (or value) of the factor changes or remains constant during the course of the event (response to an accident).

Perceived raw information is temporarily stored in the WM and serves as the stimuli to change the MS. The stimuli is amplified or damped after passing through the operator's intrinsic psychological characteristics and other factor that could function as a "cognitive filterers", before being appraised.

The combination of cognitive process and observable actions of an operator during the course of an accident is a continuum. The entire process may be divided into smaller phases in terms of dominant goals or modes of response such as situation assessment search for the cause, and selection and execution of the response and recovery plan. Each of these phases can be further divided into sub-phases (e.g., following specific segments of a procedure) with specific and distinct cognitive and behavioral characteristics. IDAC covers this continuum in form of a set of discrete cognitive events such as the steps associated with processing of the incoming information, goal selection, and selection and execution of problem solving strategies to achieve the goal. The dynamic process controlled and powered by the cognitive engine continues as a series of loops (Figure 2-3) covering these cognitive basic events throughout the course of crew response to an evolving situation. In the current trail applications of IDAC, a particular level of detail for the cognitive basic events is chosen that is consistent with the currently limited content and structure of the KB. Given the flexibility of the layered architecture and model decomposition using embedded I-D-A units, the fidelity and resolution of the model is a matter of modeler's choice and a function of the intended use of the model.

2.5.3 Response Probabilities

The cognitive basic events and the resulting observable behaviors (closing a valve, skipping a procedural step) are not deterministic. IDAC considers alternative paths and outcomes for the various response steps (cognitive and outward behavior), each with an assigned conditional probability. At each option points, the list of options or alternative paths is assumed to be exhaustive and, therefore, the sum of the corresponding probabilities is 1. These probabilities are conditional on the context, including the sequence of preceding events, and their values are calculated as a function of the states of various model parameters and variables, including dynamic and static factors, and incoming information. Therefore, the probabilities cover a mix of model uncertainty, epistemic uncertainty of the model parameters, as well as the aleatory variability in the input variables.

In current applications of IDAC, qualitative and quantitative scales are used to assess the state of input variables and parameters (e.g., PFSs), which in turn are used to calculate the probability for each alternative outcomes. Values of static PSFs are the inputs to the model, and are quantified by the HRA analyst. The values of dynamic PSFs are dynamically calculated as a function of the scenario context, and static PSFs. For quantification of the static external PSFs, IDAC uses the conventional methods, such as expert judgment and surveys. In one implementation of IDAC, some of the psychological PSFs are assessed using a demand-resource model, where the psychological load is associated with the perception of relative magnitudes of the demand and available resources to meet it. In some cases the magnitude or indicators of demand and resource can be measured or estimated directly. In other cases, surrogate measures may be used, since the related variables are not directly observable.

2.5.4 Errors from IDAC Perspective

It is evident that errors and failures attributed to human, hardware, or software are only recognizable in context. Closing a valve might be an error in one context, and success in another. Similarly, skipping a procedural step, which might constitutes a violation of the prescribed response, could be the correct action for the specific situation at hand. This has been recognized by all HRA approaches, old and new. By applying IDAC, operator cognitive response and actions are identified which depending on the context might be labeled as correct or erroneous. Based on the original form of the IDA model [21], [22], a set of model-based criteria has been developed for characterization of operator errors. These criteria were used as the basis of error taxonomy for retrospective analysis of events, and for evaluation of the results of IDAC-based analysis of PRA scenarios. Errors are identification with respect to two sets of reference points: external and internal (Figure 2-4).

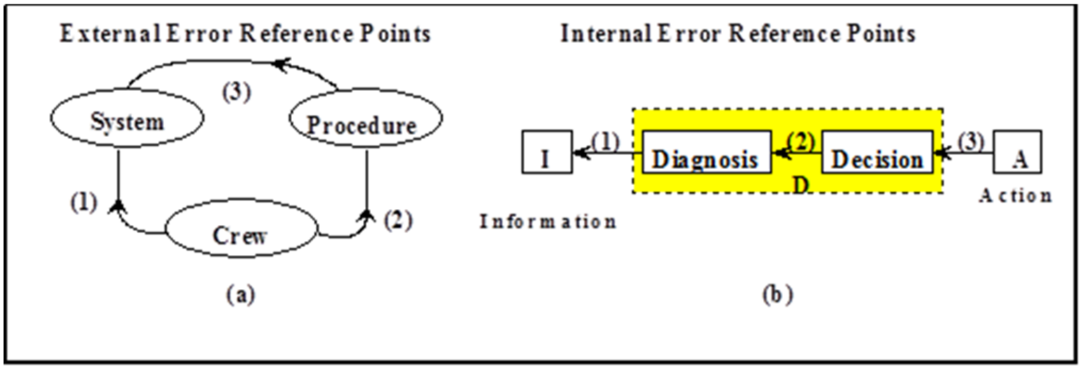


Figure 2-4: IDAC-Based Error Reference Points

An observable human action can be classified as an error with respect to the external reference points: the system, procedures, and the crew. As seen in Figure 2-4a,

- crew behavior is compared with the system needs or actual system state,
- crew behavior is compared with the procedure requirements, and
- procedure requirements are compared with the system needs

Any mismatch between the states and mutual requirements of any two reference points can be classified as an error. Since the definition of errors is difficult and is always context-dependent, these reference points should not be viewed as rigid rules to define errors.

The three internal error reference points correspond to the three main elements of IDAC, i.e., Information Module, Problem Solving/Decision Making Module, and Action Module. These internal reference points (Figure 2-4b) allow tracing the observable human action back to the cognitive stage where the error originated and then down to the influencing factors that affect the operators' cognitive and physical abilities. The premise of the internal reference points is that the error has occurred in the module where a correct input resulted in incorrect output. A detailed taxonomy and root cause analysis have been developed based on the above reference points.

3 Overview of Phoenix HRA

This research started with the framework for the Model-Based HRA that had been proposed by Mosleh et al. in [6], [23] and developed the building blocks, complete methodology and procedure for its implementation. This chapter provides a road map through the research by briefly discussing the elements of the qualitative and quantitative analysis phases of the methodology and how this research has either developed or contributed to its development. This is done by summarizing the content of the subsequent chapters in this dissertation.

3.1 Overview of the Qualitative Analysis Framework

The qualitative analysis framework is made up of three main layers namely:

- Crew response tree (CRT): This is a forward branching tree which provides a systematic coverage of the crew-plant interaction scenarios that is consistent with the scope of the analysis defined in the PRA model.
- The human response model: The human response model adopted for this work is the Information, Decision and Action Model (IDA). It is a cognitive model which is used to relate the crew failure modes (CFMs) to the crew responses modeled in the CRT. It is modeled using fault trees.
- Performance influencing factors (PIFs): PIFs are factors that enhance or degrade human performance. They are related to the CFMs using a causal model.

The framework layers and its relationship to a typical PRA model is shown in Figure 3-1. The CRT is synchronized with the PRA model as indicated by the green time arrow. It serves as a supporting tree to the PRA model by providing causal explanations of the HFE of interest. The dash lines which link the CRT to the PRA model serve as causal explanations and aid the HRA analyst in keeping track of the relationship between the PRA and CRT scenarios. The lines are not formal mathematical links.

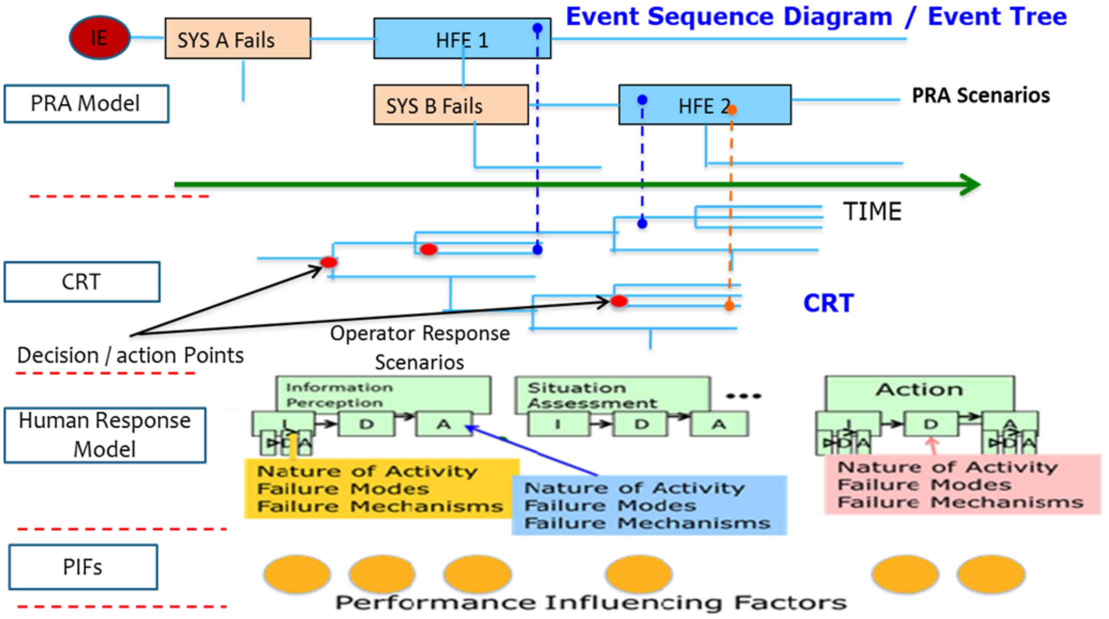


Figure 3-1: The qualitative analysis framework layers and a typical PRA model

Each layer of the framework has major elements / building blocks as indicated in Figure 3-2. These elements have been developed or improved as part of this research and will be discussed in detail in the subsequent chapters of this dissertation.

3.1.1 Elements of the top (CRT) layer

The elements of the CRT layer are discussed in Chapters 4 and 5 of this dissertation. Chapter 4 provides a road map to the qualitative analysis process. It discusses the procedure steps and sub steps required to conduct the qualitative analysis. It contains the guidelines which have been developed as part of this research work to aid the HRA analyst in task analysis. Task analysis is conducted in the context of the PRA model, CRT, IDA task decomposition, and the crew activities. A catalog of the types of information needed in support of the analysis process which have also been developed as part of this research is being provided as well. The output of the analysis process include; qualitative insights and narratives for HFE scenarios, CFM cut-sets, and PIFs relevant to the HFE scenario.

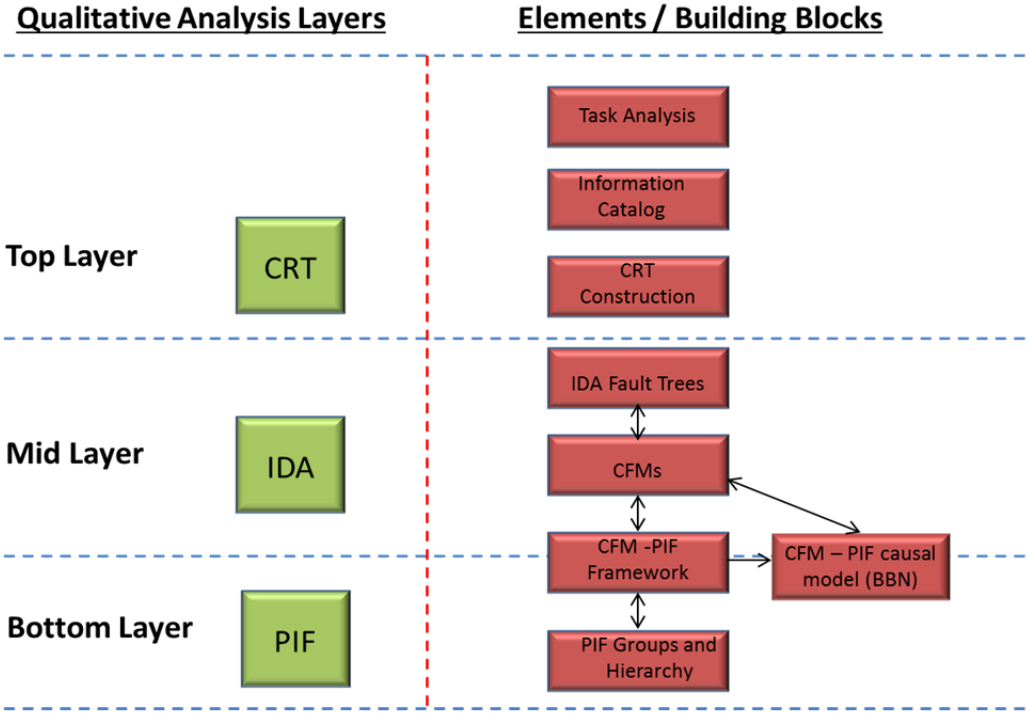


Figure 3-2: Qualitative framework layers and Building Blocks

Chapter 5, we discuss the CRT development. It provides the guidelines and a flow chart to aid the construction process. The flow chart has accompanying tables that contain the questions for creating it and the branch point description. Also, discussed are the incorporation of the timing of crew responses and the crew's ability recover from error as branches in the CRT. The ability to assemble different "function-level"

CRT modules through simple merge rules to build larger and more comprehensive CRTs is also covered in chapter 5. As part of this research, the initial CRT flow chart structure has been modified and the timing of crew responses has been incorporated to enhance consistency and completeness of the constructed CRT.

3.1.2 Elements of the mid (IDA) layer

Chapter 6 discusses the human response model (IDA) fault trees (FTs). The FTs are used to model the human failure mechanisms and the modes of crew failure. HFEs or contributing causes can be traced through the I-D-A chain using the information-processing model. It aids in the identification of HFEs and scenarios leading up to the HFEs. They are used to link the CFMs to CRT branches. As part of this research, the structure of the FTs has been modified and also expanded to include the set of CFMs that we have developed.

As part of this work, we developed a comprehensive set of CFMs, discussed in chapter 6. They are used to further specify the possible forms of failure in each of the IDA phases. They represent the manifestation of the crew failure mechanisms and proximate causes of failure and are selected to cover the various modes of crew response including procedure driven, (PD), knowledge driven (KD), or a hybrid of both (HD). The CFMs form the basic events in the IDA FTs.

3.1.3 Elements of the bottom (PIF) layer

A set of PIF groups and hierarchy that we developed during this research work for use with this methodology is discussed in chapter 8. It was developed based on efforts in trying to consolidate and relate to the roots of psychological evidence and the best set of PIFs currently used in HRA. The PIFs are grouped in terms of front line factors that directly affect crew performance. Each PIF group is made up 2 to 3 PIF levels. The lower level PIFs are either types or attributes of the PIFs in the higher level. This hierarchical structure provides the ability to incorporate data into the analysis at the required level of detail.

Chapter 9 covers the CFM-PIF framework that we developed as part of this research, for relating CFMs to PIFs based on possible causes of failure and mechanisms for human error. It provides a means for developing a structured, causal model. It has been developed based on extensive literature review of psychology, cognitive sciences, operating experience and expert inputs sponsored by the US NRC.

The BBN model development is discussed in chapter 10. This model is developed as part of this work and it based on the CFM-PIF framework to model the effects of the influence of PIFs on crew performance. The nodes in the model are made up of CFMs and PIFs, and this model has the flexibility to be modified for interfacing with existing HRA methods like SPAR-H.

3.2 Overview of the Quantification Framework

Figure 3-3: The Quantification framework overview

The quantification phase includes; the process of gathering the data required as input to the CFM – PIF BBN model, the analysis of the gathered data, and the quantification of the CFM – PIF BBN model to obtain the conditional human error probability (HEP) estimate. The inputs to the quantification process include the CFM minimal cut-sets and the PIFs that had been identified as being relevant to the HFE scenario during the qualitative analysis. Note that the entire quantitative analysis framework and process is being developed as part of this research work.

The overview of the quantitative analysis process is given in chapter 11. It provides the ability to incorporate dependency between CFMs and/or HFEs into the analysis. We present the integrated model which is made up of the CRT, FTs and BBN. This model can be quantified using the Integrated Risk Information System (IRIS) software tool. This tool was built by the Center for Risk and Reliability at the University of Maryland, College Park to support PRA and safety monitoring of complex socio-technical systems. It uses a three-layer hybrid causal logic (HCL) modeling approach. Its 1st layer, the event sequence diagram (ESD) layer is used to construct the CRT sequences, 2nd layer, FT layer is used to build the FTs, and the 3rd layer, BBN layer is used to build and quantify the BBN model.

Chapter 12 discusses the quantification of the BBN model. We provide an overview of the BBN quantification process and discuss the benefits of using the BBN as our quantification model. Also covered in this chapter is the methodology for assessment and estimation of PIF levels. The PIF levels are a part of the required model inputs. Finally, we present the methodology steps for BBN model quantification. These are the set of steps which the analyst needs to follow in order to estimate the conditional HEP of an HFE.

Chapter 13 discusses HFE dependency modeling and quantification. The issue of dependency has not been adequately addressed in HRA. We provide a methodology for the explicit treatment of dependencies among HFEs using the time slice concept of Dynamic Bayesian networks (DBNs) and the BBN model. We also use an example case to illustrate the methodology steps.

In chapter 14, we discuss the data gathering and analysis process in order to provide estimates for our model parameters. There is no single source that can provided all the information required in our model. Therefore, we had to incorporate data from various sources into our model parameter estimation process using the Bayesian methods. The data sources include other HRA methods, NPP operating experience, and expert HEP estimates.

In chapter 15, we provide examples to demonstrate the complete application of our methodology (Phoenix HRA), including various important concepts developed as part of this research. Since the specific instance of this methodology is applicable to NPPs, the examples presented are tailored towards applications like that of accident sequence precursor (ASP) analysis, significant determination process (SDP) (events that involve performance deficiencies), event assessment. We use an ASP analysis example to demonstrate our entire qualitative and quantitative analysis methodology.

This research work is summarized and concluded in Chapter 16. We present the foundation of both phases of Phoenix HRA, the contributions of this research, the attributes of the methodology compared to what is required of a robust HRA method, challenges faced in the course of this work and suggestions for future improvements.

4 Overview of the Qualitative Analysis Process

The HRA qualitative analysis process broadly involves the identification of human failure events (HFEs) and the characterization of crew-plant scenarios that lead to the HFEs. Generally, it is assumed that the starting point for the qualitative analysis is the identification and definition of the human failure events (HFEs). This process can be generically defined as a four-step process [25] namely:

- **Identification and Definition of the HFE and its PRA Scenarios Context**: One of the main objectives of HRA is the identification of HFEs, which are a result of an iterative process of developing PRA scenarios. The set of HFEs should represent those needed to model the impact of potential human failures on the accident scenario progression. An HFE definition may include the failure of the crew action described in relation to the function which they needed to achieve, the PRA scenario in which the HFE is modeled, the physical plant condition by which the crew's action must be completed, and the manipulations that must be performed in order to achieve the required function. Note that the PRA scenario specifies the initiating event, hardware and crew action events that would lead up to the demand for the specific crew action. The preceding successes and failure events are relevant for the HRA because they aid in determining the context for the crew action as well as influencing the time evolution of the physical plant parameters [39]. Also, this step may involve refining the definition of the HFE. In other words, it may be necessary to decompose the identified HFE into sub-HFEs. For example, it may desirable to define HFE-FB={Failure to Perform Feed and Bleed} as HFE-F= {Failure to Perform Feed} and HFE-B={Failure to Perform

Bleed}. For each HFE, the analyst needs to understand the scenario and the context that affects it. The analyst also needs to understand which procedures, intended and otherwise, the crew might use in the specified scenario.

- **Task Analysis**: This step of the qualitative analysis process involves the identification of the subtask associated with the crew's cognitive processes and physical actions in relation to the specific HFE of interest. Task analysis is also used to aid in identifying both the opportunities for incorrect responses, and opportunities for recovery after the incorrect responses are made.
- **Identification of Failure Causes**: The aim of this step of the analysis is to identify the potential causes of human error which could lead to the failure of the specific HFE of interest. These causes of human error are referred to as crew failure modes in our methodology.
- **Assessment of Influence of Context**: The aim of the final step of the analysis is to identify and assess the factors that influence the likelihood of the occurrence of human error by increasing or decreasing it. We refer to these factors as performance influencing factors (PIFs) and they are derived from context provided by the crew conditions, plant scenarios and environmental factors.

The above steps, captured through appropriate tools and techniques, are reflected in the following process flow diagram (Figure 4-1). The diagram recognized two distinct possibilities as the starting point of the analysis: (1) HFEs are identified as part of an existing PRA model, or (2) HFEs are to be identified in an iterative process.

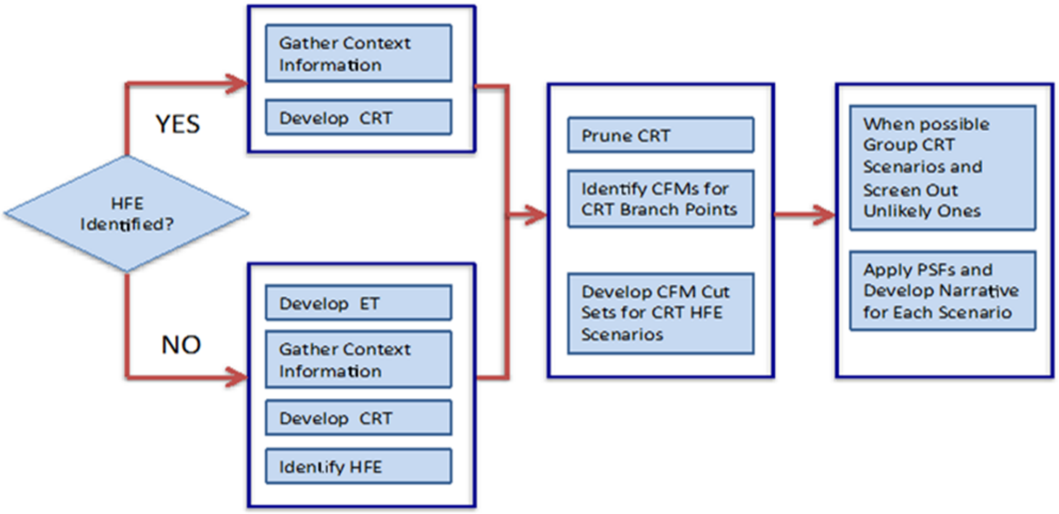


Figure 4-1: Qualitative Analysis Process overview

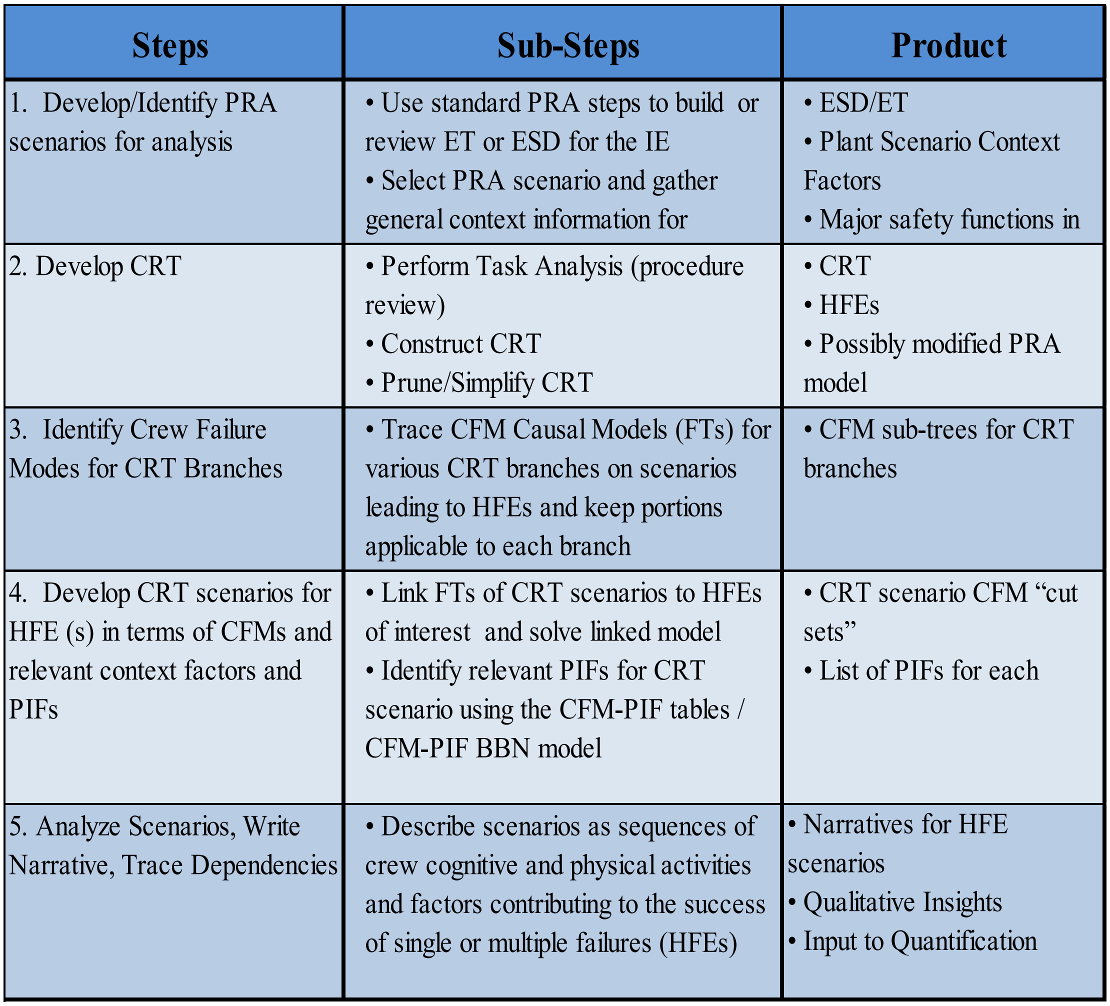
4.1 Summary of the Analysis Procedure

The main steps of the Qualitative Analysis Procedure are:

- Step 1: PRA Scenario Development/Familiarization
- Step 2: Development of Crew Response Tree
- Step 3: Identification of Crew Failure Modes for CRT Branches
- Step 4: Construction of HFE Scenarios
- Step 5: Analysis of HFE Scenarios, Development of Narratives, and Identification of Dependencies

Important sub-steps and products of the steps are summarized in Table 4-1. The steps and sub-steps are described in more details in the following sections [27].

Table 4-1: Major Steps and Products of the Qualitative Analysis Procedure



Steps	Sub-Steps	Product
1. Develop/Identify PRA scenarios for analysis	• Use standard PRA steps to build or review ET or ESD for the IE • Select PRA scenario and gather general context information for	• ESD/ET • Plant Scenario Context Factors • Major safety functions in
2. Develop CRT	• Perform Task Analysis (procedure review) • Construct CRT • Prune/Simplify CRT	• CRT • HFEs • Possibly modified PRA model
3. Identify Crew Failure Modes for CRT Branches	• Trace CFM Causal Models (FTs) for various CRT branches on scenarios leading to HFEs and keep portions applicable to each branch	• CFM sub-trees for CRT branches
4. Develop CRT scenarios for HFE (s) in terms of CFMs and relevant context factors and PIFs	• Link FTs of CRT scenarios to HFEs of interest and solve linked model • Identify relevant PIFs for CRT scenario using the CFM-PIF tables / CFM-PIF BBN model	• CRT scenario CFM “cut sets” • List of PIFs for each
5. Analyze Scenarios, Write Narrative, Trace Dependencies	• Describe scenarios as sequences of crew cognitive and physical activities and factors contributing to the success of single or multiple failures (HFEs)	• Narratives for HFE scenarios • Qualitative Insights • Input to Quantification

In general, the objectives of Steps 1 and 2 (in part) are to identify and incorporate HFEs (which, in a PRA context, are defined as functional failures, such as failure to initiate feed and bleed before core damage occurs) into a PRA. If the PRA models (ESD/ET and corresponding FTs) exist and HFEs are identified, Step 1 of the qualitative analysis primarily becomes the process of analysts gaining familiarity with the PRA scenarios leading to the HFEs and gathering the needed information to support construction of the crew response tree and completion of other qualitative analysis steps. Otherwise, the analysis starts with development of the PRA models and, ideally, concurrent and iterative development of CRTs. When starting with an existing HFE, the process may indeed lead to the modifications of the HFE or the addition of new ones to the PRA.

In the remainder of this chapter, we will discuss our task analysis process and provide some information required to support the qualitative analysis process. In the subsequent chapters of this dissertation, we'll discuss in detail the other steps and sub-steps of the qualitative analysis procedure which include the development of the CRT and CFM causal models, CFMs and PIFs used in the model, and the CFM – PIF causal model.

4.2 Task Analysis

A task is a set of human behaviors or actions which are necessary to accomplish a system goal, independent of the individual that is performing it. In the NPP, crews are assigned various tasks which need to be completed for the smooth running of the facility. Each task can be decomposed into multiple sub-tasks and each sub-task into more sub-tasks and so on. Hence, there is a need for a set of guidelines to aid in conducting task decomposition.

Task analysis is a formal and systematic approach used to describe the physical actions and cognitive processes required by the crew in order to achieve the overall system goal [26], [28]. It creates a picture of the extent of human involvement given a certain task, and uses the information that is necessary for an analysis to the extent of adequacy required of that involvement. It describes the activities involved in completing a task. One of the main issues in task analysis is determining where to stop task parsing i.e. determining when to stop decomposing the task into sub-tasks in order to obtain the right level of detail required for the analysis. This is necessary to promote consistency and traceability among different analyst using this methodology and also to prevent the analysis being done at different levels of abstraction. Hence, guidelines for task analysis is provided to aid in identifying the sub-tasks (at the right level of detail) associated with crew's actions and cognitive processes related to the specific HFE of interest.

4.2.1 Task Decomposition

A task can be described starting from the overall system goal(s) and then breaking it down to the level of individual operations. In order to successfully perform this decomposition, the analyst needs to consider the functional, cognitive and procedural requirements of the task to be analyzed.

The crew response tree (CRT) is a tool used for task decomposition of the particular safety function of interest. The functional requirements are covered in the CRT flowchart construction process by decomposing the safety function (which can be considered the overall system goal) into individual crew member actions. This is accomplished by using the questions which guide the addition of branches to the CRT. Procedures are used to provide explicit step-by-step guidance required by the crew in completing the safety function.

In addition to the CRT, the human response model (IDA) is also used as a vehicle for task decomposition. The phases of the IDA model cover subdivisions such as Noticing/ detecting /understanding, Situation assessment / diagnosis, Decision making / response planning, and Action taking. Within each of the IDA elements, a nested I-D-A structure may exist; that is, each phase of the IDA model may be decomposed into sub I-D-A structures. Each phase of the sub I-D-A structure can also be decomposed into other sub I-D-A structures and so on. The level of decomposition of these IDA elements depends on the amount of detail needed for the task analysis and parsing of different human activities into 'sub-events" or sub-tasks (Figure 4-2). In addition to the nested IDA structure, the human response model has both cognitive and physical requirements embedded in it. As indicated in the fault tree representation of the model, the crew is either adhering to the procedures or relying on their knowledge as the strategy for performing their assigned task at any given time.

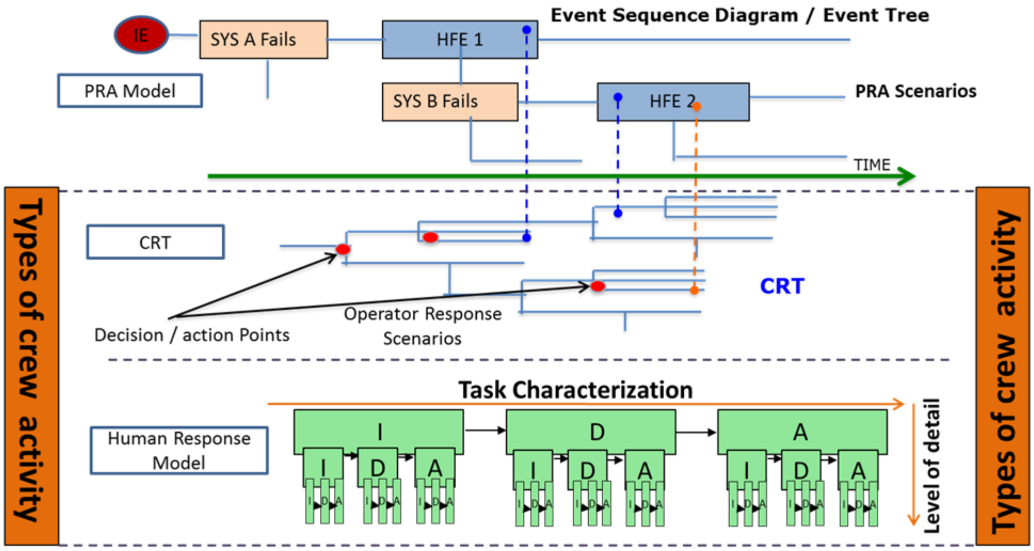


Figure 4-2: Representation of the flow of Task analysis

Connected together, both modeling tools (the CRT and associated fault trees) in conjunction with the PRA model provide the flow of task analysis. Together, they provide the analyst with the information on what to consider in the task analysis. This mixture of procedures, cognitive and physical processes, and system interface aid in the breakdown of the crew's response to an identified safety function. It implies a certain level of detail at the system, and the functional interface between the system and the crew.

The PRA model also imposes a certain level of detail. The CRT is used to model the crew-plant interaction scenarios and for identifying the HFEs while the fault trees are used to represent the human response model where the HFE is the top event and the CFMs form the basic events. Therefore, the analyst can use the CFMs as an aid in identifying the level of task definition since it is the basic task unit used in estimating HEPs in our methodology.

4.2.2 Crew activities

In the task analysis process, each task can be decomposed into different task steps and these task steps can be characterized in terms of the activities that are involved. We have provided a set of activities to serve as a guide to the entire process as shown in Figure 4-2. These set of activities (see Table 4-2) represent the types of activities generally carried out by the crew (types of crew activities). These set was adopted from the extended version of CREAM [12], and we have expanded it to include other specific activities that we consider relevant in crew's interaction with the plant or system.

When combined with our human response model (IDA), each crew activity can be associated with the different IDA phases i.e. Information processing, Decision making and Action taking (see Table 4-3). We assume that in their interactions with the plant, the crew carries out four main functions namely: Noticing/ detecting / understanding, Situation assessment / Diagnosis, Decision-making / Response planning, and Action taking. These functions correspond to different IDA phases, noting that the D phase has been decomposed into situation assessment/ Diagnosis and Decision making / response planning for simplicity. It can also be merged together as needed.

Table 4-2: Types of Crew Activities and Definitions

Types of crew activities	Definitions
Monitor	To follow the development or keep track of system parameters / states, indicators, alarm activations, annuciators over a period of time.
Scan	To quickly or speedy review of displays, indicators or other information source(s) to obtain a general impression of the state of a system or individual parameters.
Detect / Observe	To discover or read specific measurement values, key alarm activations, annuciators, indications, procedures and changes in the state of the system in general.
Identify	To establish the identity of the state of a plant or parameter which may involve specific operations to retrieve information and investigate details. It also involves choosing the right procedure to use or step to follow in completing a task."Identification" is a more thorough activity than "evaluation".
Communicate	To transfer information needed for system operation between crew members. This is done by either verbal, electronic or mechanical means. Communication is an essential part of crew response.
Evaluate / Interprete	To appraise or assess an actual or hypothetical situation, based on available information without requiring special operations. It also involves assessing crew actions like procedure transfers etc. Other related terms are "inspect" and "check".
Record	To write down or log system events, measurements and other related plant information.
Compare	To examine the qualities of two or more entities (plant / system information, events, parameters) with the aim of discovering similarities or differences. This comparison may require some form of calculation.
Verify	To confirm the correctness of a system /parameter condition or measurement, either by inspection or test. It includes the review of previous information gathered about the system or parameter, which could be in the form of feedback from prior operations . Verification also includes confirming the use of the correct procedure or procedure step for the task being performed (by the crew).
Adapt	To adjust to a changing plant / parameter state or condition e.g. adapting a set of procedure to the current plant condition.
Diagnosis	To recognise or determine the nature or cause of a condition by means of reasoning about its signs or symptoms or by the performance of appropriate tests. "Diagnosis" is a more thorough activity than "identification".
Decide	To knowningly choose a certain course of action like choosing to collect a certain piece of information or not. This may be based on some preconceive notions or ideas.
Plan	To formulate or organise a set of actions (either long-term or short-term) by which a goal will be successfully achieved.
Coordinate	To bring system states and/or control configurations into the specific relation required to carry out a task or task step e.g. allocating or selecting resources in preparation for a task/job, calibration of equipment, coordinating activities among crew members, etc.
Execute	To perform a previously specified action or plan e.g. opening/closing control valves, starting /stopping pumps, filling/draining tanks, etc.
Regulate	To alter the speed or direction of a control (system) in order to attain a goal e.g. positioning plant parameters to reach a target state.
Maintain	To sustain a system plant in a specific operational state. Note that this is different from maintenance which is generally an off-line activity.
Adhere	To follow procedures and instructions for carrying out assigned task or specific course of action.

Table 4-3: Relationship between types of Crew Activities, CFMs and IDA phases

Types of crew activities	Human Response Model (IDA)																		
	Information Processing (I)									Diagnosis/Decision making (D)							Action Taking (A)		
	Noticing/ Detecting / Understanding									Situation assessment / Diagnosis			Decision making / Response planning				Action taking		
	I1	I2	I3	I4	I5	I6	I7	I8	I9	D1	D2	D3	D4	D5	D6	D7	A1	A2	A3
Monitor	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫										
Scan	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫										
Detect / Observe	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫										
Identify	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩							
Communicate	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟥	🟥	🟥
Evaluate / Interprete	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩							
Record	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩							
Compare	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩							
Verify	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩							
Adapt										🟩	🟩	🟩	🟧	🟧	🟧	🟧			
Adhere	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟥	🟥	🟥
Diagnosis										🟩	🟩	🟩							
Decide	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟥	🟥	🟥
Plan													🟧	🟧	🟧	🟧			
Coordinate	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟥	🟥	🟥
Execute																	🟥	🟥	🟥
Regulate																	🟥	🟥	🟥
Maintain																	🟥	🟥	🟥

I1: Key Alarm not Responded to (intentional & unintentional)	D1: Plant/System State Misdiagnosed
I2: Data Not Obtained (Intentional)	D2: Procedure Misinterpreted
I3: Data Discounted	D3: Failure to Adapt Procedure to the situation
I4: Decision to Stop Gathering Data	D4: Procedure Step Omitted (Intentional)
I5: Data Incorrectly Processed	D5: Deviation from Procedure
I6: Reading Error	D6: Decision to Delay Action
I7: Information Miscommunicated	D7: Inappropriate Strategy Chosen
I8: Wrong Data Source Attended to	A1: Incorrect Timing of Action
I9: Data Not Checked with Appropriate Frequency	A2: Incorrect Operation of Component/Object
	A3: Action on Wrong Component / object

Each crew activity can be described in terms of any of the combinations of the four functions it requires (Table 4-3). For example, a task step that requires the crew to compare certain aspects of the system performance will primarily involve Noticing/ detecting / understanding and Situation assessment / Diagnosis functions and this is indicated by shading the corresponding cells. Also since the crew (and not the individual operator) is the unit of analysis in our methodology, activities like communicate, adhere, decide and coordinate are considered to involve all four functions.

Each crew activity can be used to characterize a task step and in some instances, a task step may be characterized by more than one crew activity. We have also included our CFMs I1 – A3 to aid the HRA analyst in identifying the predominant failure modes that can be associated with a particular crew activity. As an example, during a "comparing" activity, the predominant failure modes should be from any of those under the Noticing/ detecting / understanding and Situation assessment / Diagnosis functions.

4.2.3 Basic Guidelines for Task Decomposition

There are no hard and fast rules on where to stop task parsing i.e. the right level of detail required for the task analysis. However, we are providing some guidelines on which the analyst could base his or her decision. The level of task decomposition required for task analysis can be based on:

- The level of detail required in the PRA model. In order to be consistent, the analyst can base the level of detail in the task analysis on that of the PRA model.
- The resources available for modeling and conducting the analysis. This may affect the level of task decomposition because if the analyst has sufficient time and resources allocated for conducting the analysis, he or she may decompose the task into more levels of detail as opposed to when limited or insufficient time is available.
- The HRA requirements and purpose of the analysis. The requirements specified and the purpose of the analysis would aid the analyst in determining the right

level of task decomposition required. However, we recommend that task parsing should be continued at least till the analyst gets to the subsystem level. Thereafter, he or she may decide if the component level of detail is necessary or not.

- The amount and type of information available. The amount and type of information available for the analysis would aid in determining the level of task decomposition. For example, if there is a lot of information available at the component level of the system, the analyst may be able to conduct the analysis at this level. However, if little or no information is available at this level but there is enough at sub-system level, the analyst will likely carry out the analysis at the sub-system level.
- The success criteria for achieving the safety function. The success criteria for achieving the safety function can aid the analyst in determining the right level of detail for task analysis. If the success criteria at the component level are significantly different for the individual components, then it is recommended to model the different components separately and conduct the analysis at the component level. Otherwise, the analyst can stop at the subsystem level or merge the respective components and model them together. For illustrative purposes, a hierarchical task analysis (HTA) is used to represent the task (safety function) – Heat sink removal (Figure 4-3). This task can be accomplished by using the auxiliary feed water system (AFW), main feed water system (MFW) or the feed and bleed system (F&B). The MFW is made up of the main feed water and condenser pump subsystems while the F&B is made up of feed and bleed subsystems. Each of these subsystems is also made up of different components as

indicated in Figure 4-3. The AFW has three components namely component pumps, water source and valves (alignment). In order to use this system to accomplish the task (heat sink removal), the crew needs to start the pumps within one hour but need to make up the water source 8 hours later. Therefore due to this significant time difference between the two human actions, we recommend that the two components should be modeled separately. However, alignment of valves and pump start can be done within the same time frame and hence, there is no significant difference in time. Therefore, the two components can be merged and modeled together.

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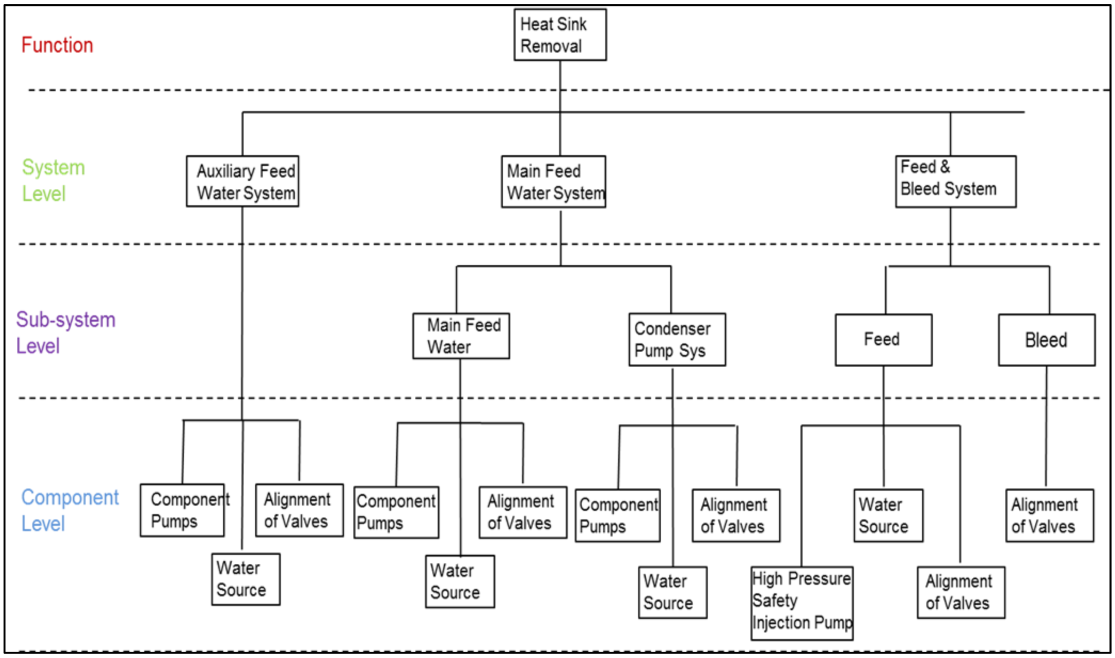


Figure 4-3: HTA representation of Heat Sink Removal

4.3 Information required to support the Qualitative Analysis Process

An HRA analyst needs to collect various types of information in order to support the analysis process. This information are generally gathered through interviews with plant and operations personnel, plant walk-through, talk-through, review of plant documents like operating procedures, plant diagrams, training manuals, etc. It includes:

- Operating instructions including those for emergency, annunciator, accident management, from the respective operating procedures
- Pictures of the interface and working environment
- General plant layout
- Engineering flow information
- Plant piping and instrumentation (P&IDs) information
- Mechanical flow information
- Information on system functions, associated systems and equipment modeled in the PRA
- System-fault information from system-fault schedules
- Interlock information from interlock schedules
- Information on prior incident through interviews with plant personnel and incident reports
- Existing task analysis from analysis reports
- Training programs from training manuals and interviews with plant personnel Operating experiences through interviews with plant personnel, operation logs
- System / equipment design specifications from installation manuals

- Crew composition in terms of size, experience level, through interviews with plant management & plant personnel

Note that this is not intended to be an exhaustive list, but to provide some guidance to the analyst on the kinds of information that may be required while conducting HRA.

5 Crew Response Tree Development

The development of a Crew Response Tree (CRT) is a key step of the qualitative analysis process. The CRT is a visual representation of the crew-plant interaction scenarios leading to HFEs as well as a structure that supports the performance and documentation of the qualitative analysis. The CRT is partly a formalization ATHEANA's "deviation" search method [29] . CRT can be devoted to finding paths to predefined HFEs and possible recoveries, or used as a vehicle to also identify new HFEs. The process can cover both Errors of Omission and Errors of Commission. CRTs can be constructed for crew response situations that are procedure driven (PD), knowledge driven (KD), or a hybrid of both (HD).

The main advantage of the CRT is that it leads analysts to perform a thorough assessment of the conditions that could lead crews to take inappropriate paths (for instance, when following procedures). This will obviously lead to a more extensive qualitative analysis and a broader consideration of the conditions that could lead crews to fail, along with different ways in which they could fail. The structure facilitates systematic identification of the so-called deviation scenarios (i.e. variations in conditions that could lead the crew to take inappropriate paths). The sub-steps involved in developing a CRT include the identification and review of relevant procedures, construction of the CRT, pruning/simplification of the CRT and the addition of HFEs to the PRA model if necessary.

5.1 Identification and Review of Relevant Procedures

For procedure-driven crew response, CRT branches include failures to perform certain steps in the procedure (i.e. the HFE can occur because of a failure to correctly follow a specific step of the procedure). Therefore, in preparing to develop the CRT, the analyst must identify and review which procedures are in play. The procedures may include the Functional Response Procedures (FRPs) and Critical Safety Functions Status Trees (CSFTs). And from an understanding of the role of the procedural steps, the analyst needs to identify the critical steps which, if not performed correctly, will lead to the HFE, unless the possibility of recovery exists.

In some cases, the failure of a specific step, which leads to a branching from the expected response, may be due to the plant parameters or system states not fully or unambiguously satisfying the decision criteria. In addition, some failures of the HFE may occur because a response path takes too long. The nature of the steps of the procedure may be different, and failure in each type is a potential contributor.

Note that not all the procedural directions are essential; some are confirmatory, and performing them incorrectly would not necessarily lead to failure. However, they may be relevant as recovery factors, and they certainly contribute to using up available time. Therefore, the branches on the CRT represent failures or successes to follow the critical steps in the procedure. On the failure branches, by walking through the procedure with an understanding of the way the plant status is changing, (particularly parameter values, potential alarms, etc.) opportunities for recovery can be identified.

5.2 CRT Construction

In order to simplify the process of constructing the CRT, a modular approach is proposed. According to this approach, CRTs are developed to model HFEs corresponding to a given safety function. Safety function may refer to the intended function of a specific plant system, a desired state of the plant or system in response to plant upset, or a combination of both. A typical event tree (ET) model includes success and failures of safety functions involved in plant response following the initiating event. Typically, crew tasks are defined in reference to delivery of the safety functions. HFEs are also defined in reference to such functions. For instance, in implementing emergency operating procedure (EOP) E-3, it is expected that the crew performs four primary tasks (for which there are corresponding HFEs):

1. Identifying which steam generator (SG) is ruptured and isolating it
2. Cooling down the reactor cooling system (RCS) by cooling the secondary loop via dumping steam
3. Depressurizing the RCS using the pressurizer spray or pressurizer PORV
4. Stopping safety injection (SI) upon indication that the SI termination criteria are met

The analysts (PRA team) determine the level of detail at which the safety functions are defined. Based on the PRA scenario, the analyst will identify the safety function(s) that play a role in plant and crew response. The HRA team needs to review the event trees and consider other gathered information regarding the HFE to decide what safety function to analyze. Sometimes, there is more than one safety function along the path to the HFE. In a modular approach to constructing CRTs, one

CRT will be developed for each identified relevant safety function. These function-based CRTs may be linked to cover the full range of an accident timeline and possible scenarios as reflected in the corresponding PRA event trees or event sequence diagrams.

A CRT is primarily constructed to represent the task decomposition. Its development involves an interdisciplinary team of PRA and HRA analysts because it requires the knowledge of the human response and plant behavior. In principle, the ET plays a similar role in HRA, although the level of detail is not usually sufficient for HRA analysis. The initial methodology for the construction of the CRTs was provided by [25]. However, it has been improved and enhanced for consistency and completeness as part of this research work. The CRT Flowchart is to be viewed as the procedure aiding the analyst in the CRT development process. The questions in the flowchart serve as a guide to the addition of branches to the CRT. Hence, the flowchart has pruning rules incorporated into its design.

In order to construct the CRT, the main inputs needed by the analyst include the HFE definition, identified safety function, crew and plant context, and all procedures used to carry out the safety function. The main output is a task decomposition of the safety function in the form of an ET, which can be used to find the failure and success paths, and the branch points of interest. This would aid in the HEP quantification.

As stated earlier, before starting the process of constructing a CRT, the analyst needs information regarding other contextual factors that could lead to the HFE by influencing the crew's ability to respond to the PRA scenario. This information can be obtained from various sources including operator and analyst experience, simulator observation, etc. The analyst is encouraged to collect additional information as needed during the CRT construction process and not wait to have a complete set of information before beginning the process. Even though the CRT represents procedurally driven task decomposition, and therefore would appear to be applicable only to internal events occurring at full power (where most of the tasks represented in the CRT involve EOPs related to the scenario), it can also be employed for other scenarios less closely linked with EOPs [25]. Figure 5-1 shows the CRT Flowchart. Table 5-1 provides a detailed description of the questions and Table 5-2 provides a description of the success and failure paths of each branch points in the CRT Flowchart.

Based on the understanding of the main inputs needed for the CRT construction, the analyst will step through the CRT flowchart to construct the CRT. He or she starts with the first question: “Is the specific function designed to be initiated automatically?” If the answer is yes, the analyst would follow the “yes-arrow” to question number 2: “Is the scenario a fast transient?” If the answer is no, the analyst will follow the “no-arrow” to question number 3: “Is there a procedure that includes monitoring and operation of the specific safety function?” If the answer to question number 2 is no, the analyst will follow the “no-arrow” to the box which says “Branch Point A”. This informs the analyst that one branch point in the CRT should be created. The branch point’s success path is “crew manually initiates the safety function before it is automatically initiated”. The failure path is “crew does not manually initiate the safety function.” If the answer to question number 2 is yes, the analyst will follow the “yes-arrow” to the box which says “Branch Point B”. The analyst creates this branch point whose success and failure paths are “The safety function is automatically initiated.” and “The safety function is not automatically initiated” respectively. By systematically stepping through the flowchart with the aid of the questions and branch point descriptions, the CRT will be fully created when the analysts reach the sixth and final question in the CRT Flowchart: “Are there additional equipment and manual actions that could be used to provide the specific safety function?” If the answer is no, the process of constructing the CRT is complete. However, if the answer is yes, the analyst will follow the “yes-arrow” to question number 3 and re-enter the flowchart from there.

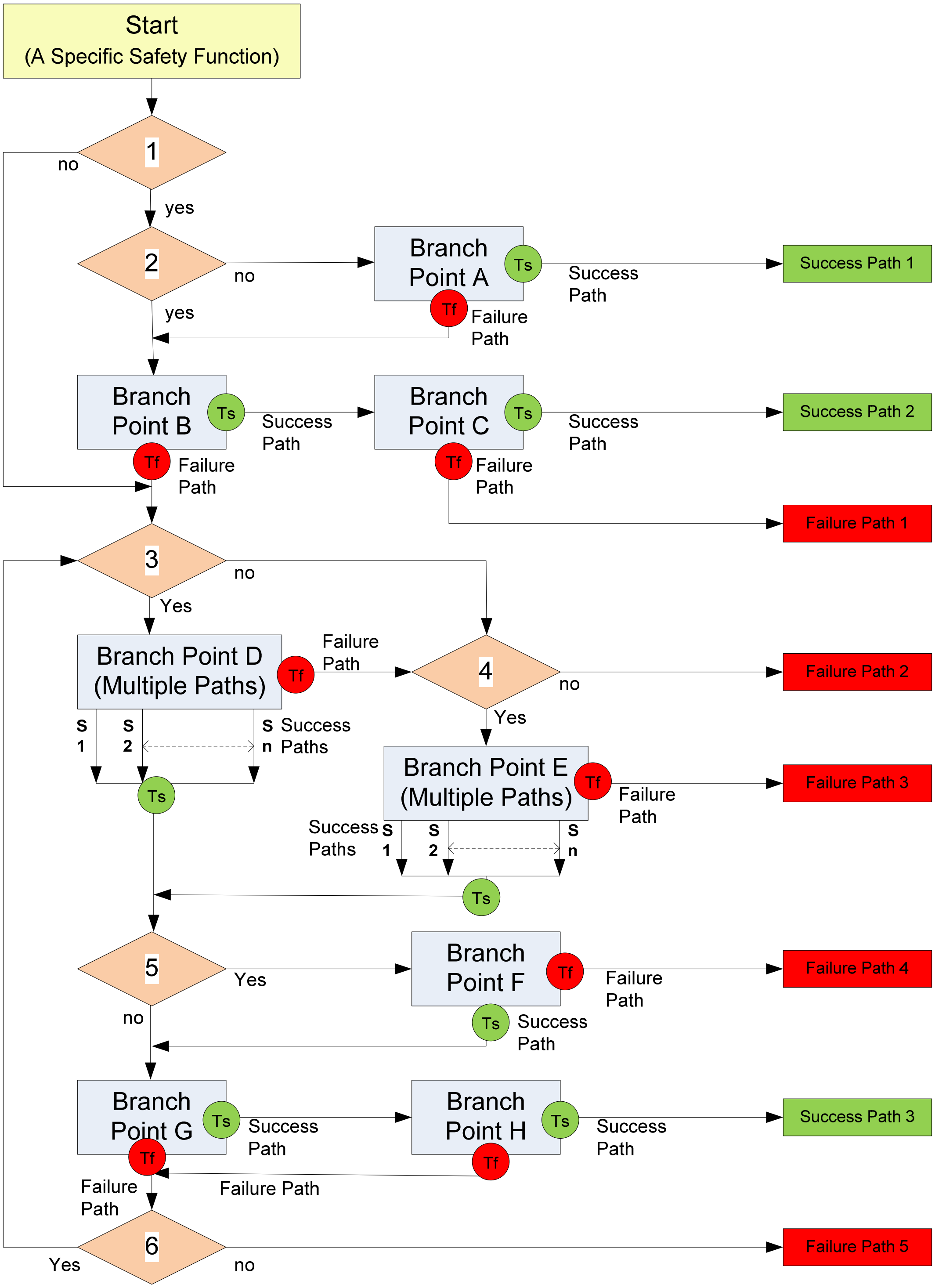


Figure 5-1: The CRT Construction Flowchart

Table 5-1: Flowchart Questions

No.	Question	Description and Example
1	Is the specific function designed to be initiated automatically?	Auxiliary Feed Water is an example of safety function designed to be initiated automatically. Isolation of a steam generator is an example of a safety function that is not designed to be initiated automatically.
2	Is the scenario a fast transient?	If loss of Main Feed Water occurs, the Auxiliary Feed Water will be automatically initiated shortly thereafter. Hence, Auxiliary Feed Water is a fast transient.
3.a	Is there a procedure that includes monitoring and operation of the specific safety function?	The answer to this question is either a "yes" or "no".
3.b	Is there a specific entry point in the current procedure to a step to manually initiate the safety function?	If there is an entry point in the current procedure to a step (or a supplemental procedure) to manually initiate the safety function, the answer to this question will be "yes".
4	Are there other procedural entry points that lead to a step to manually initiate the safety function?	The answer is "yes" if there are additional entry points in the current procedure (or another procedure to which the operator is directed to) that includes a step to manually initiate the safety function.
5	Are there any unexplored options under 3.b and 4?	If there are other options in the procedure to lead the operator to manually initiate the safety function, the answer will be "yes".
6	Are there additional equipment and manual actions that could be used to provide the specific safety function? This question refers to recovery actions that the crew could potentially take when everything else fails.	If there are other ways to achieve the same result as the safety function, the answer to this question will be "yes". If there are no opportunities for such recovery, the answer will be "no".

Table 5-2: Detailed Description of the Success and Failure Paths for Each BP

BP	Success Path	Failure Path
A	Operator manually initiates the safety function before it is automatically initiated.	Operator does not manually initiate the safety function before it is automatically initiated.
B	The safety function is automatically initiated.	The safety function is not automatically initiated.
C	Operator does not manually turn off the automatically initiated safety function.	Operator manually turns off the automatically initiated safety function.
D	This branch point considers whether the crew is in the correct procedure, various options provided by the procedure for success (i.e., multiple choices, each providing a successful path to the critical step to manually initiate the safety function, given the condition) So this branch point may produce multiple branches, each of which need to be pursued separately in the CRT. The Success Path corresponds to operator choosing a correct option for the condition and manually initiating the safety function.	Operator is not in the correct procedure, Operator is in the correct procedure but chooses the wrong option for the condition, resulting in failure to manually initiate the safety function.
E	Similar to Branch Point D.	Similar to Branch Point D.
F	Operator doesn’t transfer to the wrong direction from the exit point.	Operator transfers to the wrong direction from the exit point.
G	Safety function is not impaired by equipment (hardware / system) failure.	The safety function is impaired by non-recoverable equipment (hardware / system) failure.
H	Operators successfully initiate the safety function manually.	Operators failed to initiate the safety function manually.

5.2.1 Additional Notes on the Flowchart Questions and Branch Points

- Questions 1 and 2 determine the relevant design feature and timing of system response. Based on that, Branch Point A explores possibility of “preemptive” action by the crew.

- Branch Point B considers the possibility of failure of automatic actuation of the omission system, while Branch Point C explores the potential for an error of commission (EOC) by the crew in disabling the safety function.
- Question 3.a determines if there are procedures governing the crew response In most cases of interest, the answer to this question is "yes." The cases where there are no procedures are outside of the scope of this flowchart. Question 3.b explores whether procedure has explicit entry point to a step for manually actuating the safety system. Branch Point D expands the CRT to include cases where the crew fails to enter the correct procedure, or fails in following the correct path (possibly one of several) leading to a step to manually actuate the safety system.
- Question 4 determines if there are additional entry points in the current procedure (or another procedure to which the crew is directed to) that includes a step to manually initiate the safety function. Branch Point E is similar to Branch Point D, providing a second opportunity for the crew (response to Question 4). Therefore, this Branch Point covers cases where the crew fails to enter the correct procedure when given a new chance, or fails in following the correct path (possibly one of several) leading to a step to manually actuate the safety system.
- Question 5 makes sure that all the options listed under Branch Points D and E are covered in the analysis. If at this point the crew has reached the step to manually actuate the safety system, Branch Point F covers the possibility of the crew transferring to the wrong direction from the exit point. Branch Point G deals with the possibility that the safety function can't be actuated due to equipment

(hardware/ system) failure, while Branch Point H considers the possibility that the crew may fail in the initiation and actuation of the system.

- Question 6 determines if there are other ways to achieve the same result as the safety function. A positive answer to this question may require re-entering the flowchart through question 3.

Table 5-3: Description of Terminology Used in the CRT Flowchart

Term	Description	Examples
Automatic Action	An action taken due to automation implemented in the system	• Automatic reactor trip • Making a component in stand-by active when needed
Manual Action	An action taken by the operator, field operator, maintenance operator, etc.	• Manual reactor trip • Locally starting a piece of equipment
Action Step	A step in the procedure where an action is called out	• Identify ruptured steam generator • Check intact steam generator level
Specific Action Step	The step in the procedure that is analyzed in the specific iteration of the CRT flowchart	
Entry Point	A point in the procedure where a transfer to another relevant procedure or procedure step can be made	From Westinghouse EPGs: • Transfer to ES-1.1 from step 25e in E-0 (SI termination)
Exit Point	A point in the specific action step where a transfer to another procedure or procedure step can be made	From Westinghouse EPGs: • Transfer to E-3 from step 27b in E-0 (uncontrolled level in steam generator)
Branch Point	A point in the CRT where there is more than one option for how the scenario will play out	Transfers from one procedure to another is an example of a branch point
Function Success	Following this path will lead to success of the scenario, that is, the crew managed to recover from the HFE	
Function Failure	Following this path will lead to failure of the scenario, that is, the crew did not manage to recover from the HFE	

5.2.2 Explicit Consideration of Time

The CRT construction flowchart (Figure 5-1) produces a skeleton CRT of the main branches in reference to the plant functions and procedural steps. The variations in scenarios due to the timing of the crew's response may also be included as branch points. Generally, the crew's response is generally considered to be either successful or not as represented in the CRT construction flowchart. In this case, timing is of no significant importance. However, there are situations where the timing of their responses should be explicitly considered and these include:

- When timing has a significant impact on their next action or representation of their mental state
- When there are competing events i.e. situations where one action needs to be completed before the next one
- When there are events in sequence (whether short or long duration)
- When the current event has an impact on future events

In order to explicitly consider timing in the CRT, each success path in the flow chart can be expanded into any of the following paths: successfully finished early, successfully finished late but within the allowed time window, and hardware failure with component(s) being successfully repaired (Figure 5-2).

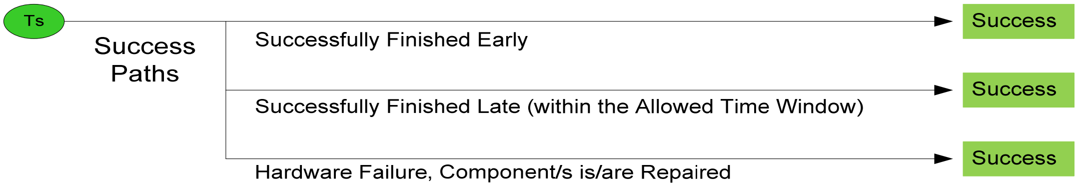


Figure 5-2: Timing in CRT Construction (Success Paths)

Also, each failure path can be expanded into any of the following paths: finished but not within the allowed time window, finished but with the wrong ordering that may cause component / system malfunction, partially finished (incomplete), no crew action, and hardware failure with component(s) not successfully repaired (Figure 5-3).

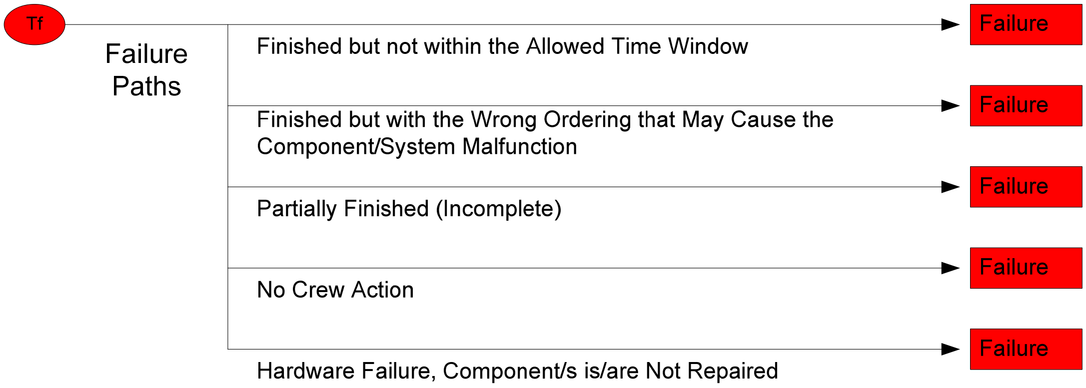


Figure 5-3: Timing in CRT Construction (Failure Paths)

Therefore, instead of the conventional binary branches of the ET (which is generally used to represent the CRT when the timing of crew response is not of significant importance), an ET with more than two branches (up to 8 branches) at each branch point can be used when timing of crew responses that need to be incorporated into the CRT construction.

5.2.3 Inclusion of Recovery

Additional branch points can be introduced for explicit consideration of recovery from CFMs. Possibility of recovery refers to the possibility that the initial fault on the part of the crew may be corrected before the failure represented by the HFE occurs (i.e. it is internal to the evaluation of the HFE). In other words, before the cliff-edge at which no correction is possible, the crew is able to recognize that their response is not working and are able to do a mid-course correction.

Some of what could be called recovery is already included as one of the PIFs, a good example being the skill-of-the-craft implementation of searching for confirmatory indications, another being the existence of an alarm that is directly related to the required response. However, in general, the possibility of recovery from CFMs can be included as branches of the CRT. We refer to this as "global" recovery. An example is when the analysts can identify the possibility that new information comes into play once the crew has deviated from the required path. It is necessary to be clear what recovery mechanisms represented are already included in the definition of CFMs. This because the ability of the crew to immediately realize and recover from an error while making it is incorporated in to the conditional probability estimate of the particular CFM. We refer to this as "local' recovery.

A high likelihood of recovery would generally be associated with scenario evolutions whose characteristics include:

- The evolution of the plant status, as determined by parameters that the crew is expected to be monitoring subsequent to the error they have made, should be sufficiently at odds with the mental picture of the plant in order to create a need to reassess whether their response is the correct one. In other words, the new evidence is strong.
- The newly revealed plant status is such that there is a plan or procedural path for correct response given a revised mental model.
- The arrival of the new information and its assimilation can happen in sufficient time to allow the correct response to be effective and prevent the HFE.

Therefore, to determine whether to take any credit for recovery, the analyst must develop an understanding of the evolution of the plant status and the expected crew behavior, following the initial incorrect response (as characterized by the descriptor for the CFMs). The analyst, therefore, should determine:

- How the plant status is changing following the error.
- What path through the procedures the crew is following, what new information will be revealed, and what does the procedure indicate about the plant status given this information.
- How the crew interacts; who's doing what and with what resources (e.g., procedures, displays).
- How the training plays into the processing of this new information.
- Whether and how the crew monitors the status of the plant to see if the plant response is as expected, e.g., if they think they are adding inventory, do they

check that level is stabilizing or increasing. This may be a parallel activity to the above.

- Establish the timeline for the new information and the necessary responses to determine if this can be achieved given the success criteria for the response.

For some cases, the identification of a recovery is quite simple. For example, in both Westinghouse and B&W procedures, if the crew member following the EOPs does not realize the need to begin feed and bleed, the crew member tracking the critical safety functions with his or her own procedure may identify the need. However, some of the more complex recoveries, particularly from errors of commission will be harder to track.

5.2.4 Combining Function Level CRTs

As indicated earlier, the CRT Flowchart methodology covers a case where the HFE is associated with a specific safety function in the context of a defined PRA scenario. The different "function-level" CRT modules can be assembled through simple merge rules to build larger and more comprehensive CRTs [6] .

Let's assume that the function "secondary heat sink control (SHSC)" is represented by CRT module 1, "Feed" is represented by CRT module 2 and "Bleed" is represented by CRT module 3 as indicated in Figure 5-4. Also, assume that the "success" end state in CRT module 1 is "Feed". The CRT flowchart can be used to construct a CRT with "Feed" as the safety function (i.e. CRT module for function 2). Also, assuming that the "success" end state in CRT module 2 is "Bleed", the CRT flowchart can also be used to construct a CRT with "Bleed" as the safety function (i.e. CRT module for function 3). Therefore, two or more CRT modules can be connected together to form a much larger and more comprehensive CRT, covering the full range of an accident timeline and possible scenarios as reflected in the PRA model.

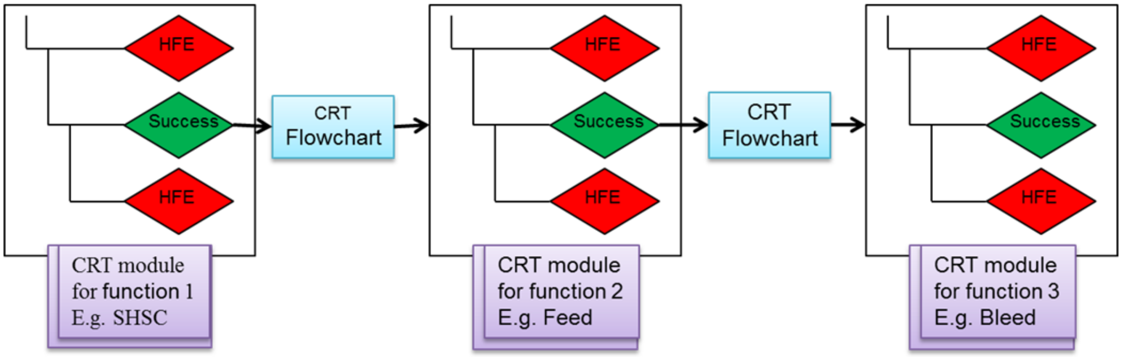


Figure 5-4: Linking of function-level CRT modules to form a large CRT

Here are some guidelines that could aid the analyst in determining whether to continue or stop developing the next CRT module from the end state of the present CRT (merge rules).

- If there is an option for recovery, use that end state as the safety function in developing the connecting CRT.
- If there is a "success" end state, use it as the safety function in developing the connecting CRT.
- If there is a "failure" end state and no option for recovery, then stop at that point and don't develop the connecting CRT.

5.3 Pruning / Simplification of the CRT

In addition to deciding which branches to keep in the tree and ultimately quantify, analysts may decide that it is reasonable to collapse some of the separate nodes or branches into a single node for quantification purposes. For example, if the impact of some end states is not significantly different (i.e. the end states are similar) the analyst may decide to merge them to become one end state. In other words, it may initially be reasonable to break-out the various failure paths to a detailed level. However, for example, it may be decided later on that the cues and related decisions for some steps in the procedures create a dependency between the steps or imply that the steps should be integrated for quantification purposes. Thus, it may make sense to quantify the branches together.

5.4 Addition of New HFEs to the PRA Model

New HFEs can be added to the PRA model if this becomes necessary.

6 Human Response Model Fault Tree Construction

The CRT branches and sequences capture some, but not all of the contextual factors and causes of crew error. In order to simplify the modeling process and analysis, the CRT branches are defined at the functional level and therefore; do not cover the human failure mechanisms or their causes [25]. HFEs or contributing causes can be traced through the I-D-A chain using the information-processing model. An error (which is the mismatch between the crew's action and plant need) could therefore be rooted in (1) action execution failure, A, given correct decision; (2) failure in situation assessment, problem solving and decision making, given correct information, D; or (3) failure in the information-gathering stage, I. Error is being defined in terms of the crew failing to meet the needs of the plant (and this is typically related to a required safety function) with focus on the functional impact of crew actions. It may be identical to HFEs defined in PRAs (as top events in the event tree or basic event in the fault tree) or one of the corresponding causes.

In this view, the "minimal cut-sets" of the human failure events are the failures in I, D, or A phases. This logic, represented in the form of a fault tree is shown in Figure 6-1.

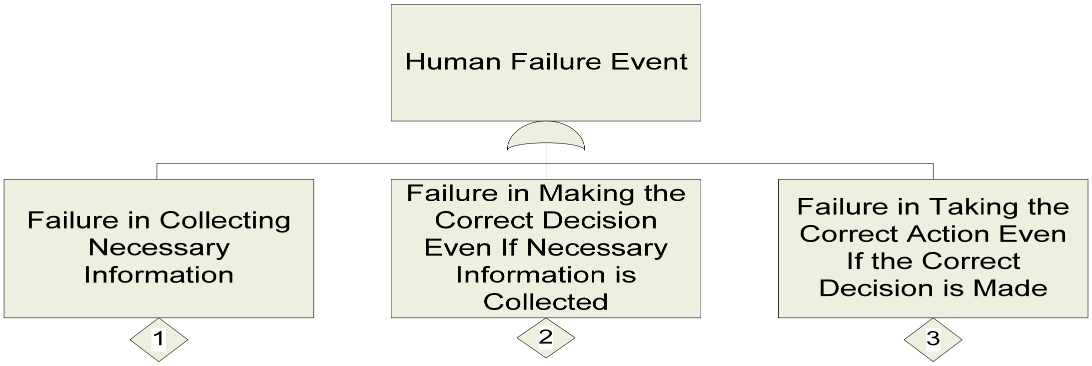


Figure 6-1: HFE logic in terms of IDA phases [6]

Potentially, all CFMs are relevant to each CRT branch point and therefore each HFE. However, when an analysis is conducted in the context of a scenario, and depending on the I-D-A phase, only a subset of the CFMs will apply. As an example, if there is no reliance on an alarm, then the CFM related to alarms "**Key Alarm Not Responded To"** will not be applicable. Therefore, an initial set of fault trees was introduced to aid the analysts in the selection of the relevant CFMs for each branch point within each scenario [25]. These fault trees were developed in order to bridge the gap between the fields of HRA and psychology/human factors and they are based on salient information from cognitive psychology literature. Using the same basis, inputs from domain experts and our judgment, we have expanded the fault trees (as part of this research work) to include all our CFMs and also improved the structure to enhance clarity and consistency. The improved and enhanced trees will serve as a better guide to the analyst in the CFM selection process. The complete list of CFMs and their definitions are discussed later in this dissertation.

The simplified cognitive model used in these FTs has three main parts as indicated in Figure 6-1. Each of this part is further broken down into FTs and based on the context related to the CRT branch point assessed, the analyst will trace through until eventually encountering an end point in the trees which represents the CFM associated with the branch point. Note that the CFMs which form the basic events in the FTs (i.e. the lowest level of the FTs) have red small circles underneath them for easy identification. Also, in some instance, a CFM can occur when the crew is following procedure and also relying on their knowledge. The crew can also switch between the procedure mode (following procedure as the strategy) and knowledge mode (relying on their knowledge as the strategy) during a specific event.

6.1 Failure in Collecting Necessary Information

In order to fail in collecting the necessary information, the crew has to fail in collecting both primary and secondary information (as indicated in Figure 6-2). Each of this failure can occur if there is a failed information source, a failure in decision to collect information and a failure in execution to collect information. The information sources include plant instruments, documents (e.g. procedures), and the crew members. The CFM representing the manner in which the crew members would fail (when considered an information source) is "**Information / Data Miscommunicated**".

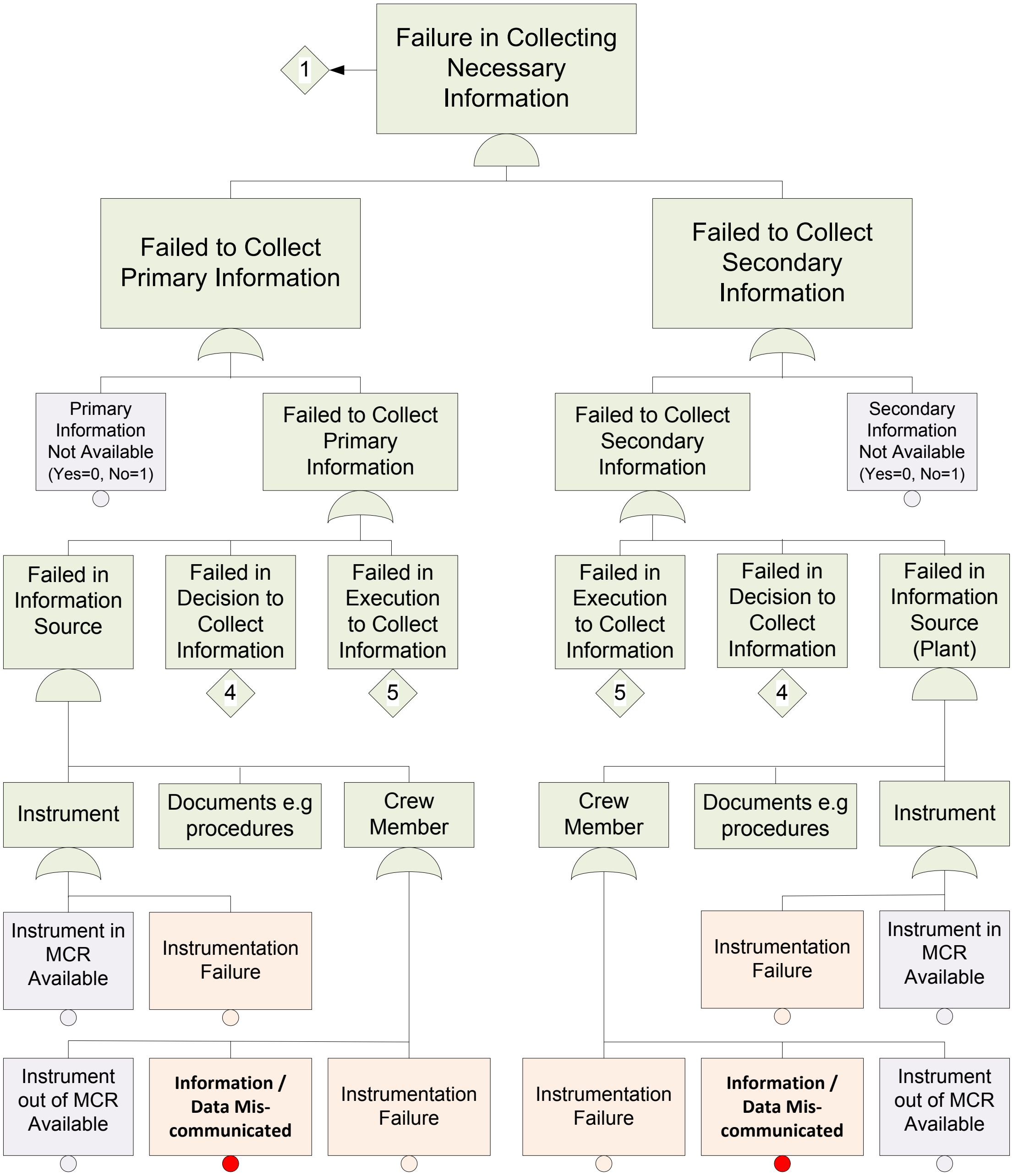


Figure 6-2: Failure in Collecting Necessary Information part of the Fault Tree

6.1.1 Failure in Decision to Collect Information

As one of the reasons why the crew may fail in collecting either primary or secondary information, the failure in decision to collect information (Figure 6-3) could occur while the crew is following the required procedures (like EOPs or when they are relying on their knowledge as the strategy for completing their assigned tasks). While following the procedure as the strategy, the crew could fail either because the guidance given by the procedure is incomplete / incorrect or because they failed to collect the active information (i.e. when the crew is directed or told to obtain the information) required to enable them complete their tasks. The CFMs representing the manner in which this failure could occur (i.e. when they have failed to collect active information) include **Data Not Checked with Appropriate Frequency**, **Data Not Obtained** and **Data Discounted**.

When the crew is relying solely on their knowledge, failure could occur because they did not collect the required passive (i.e. when the information to be collected is unexpected) or active information. The CFM representing the manner in which failure to collect passive information could occur is **Key Alarm Not Responded to (i.e. intentionally)**.When they fail to collect active information, the CFMs representing this manner of failure include **Data Incorrectly Processed**, **Decision to Stop Gathering Data**, **Data Discounted** and **Data Not Checked with Appropriate Frequency.**

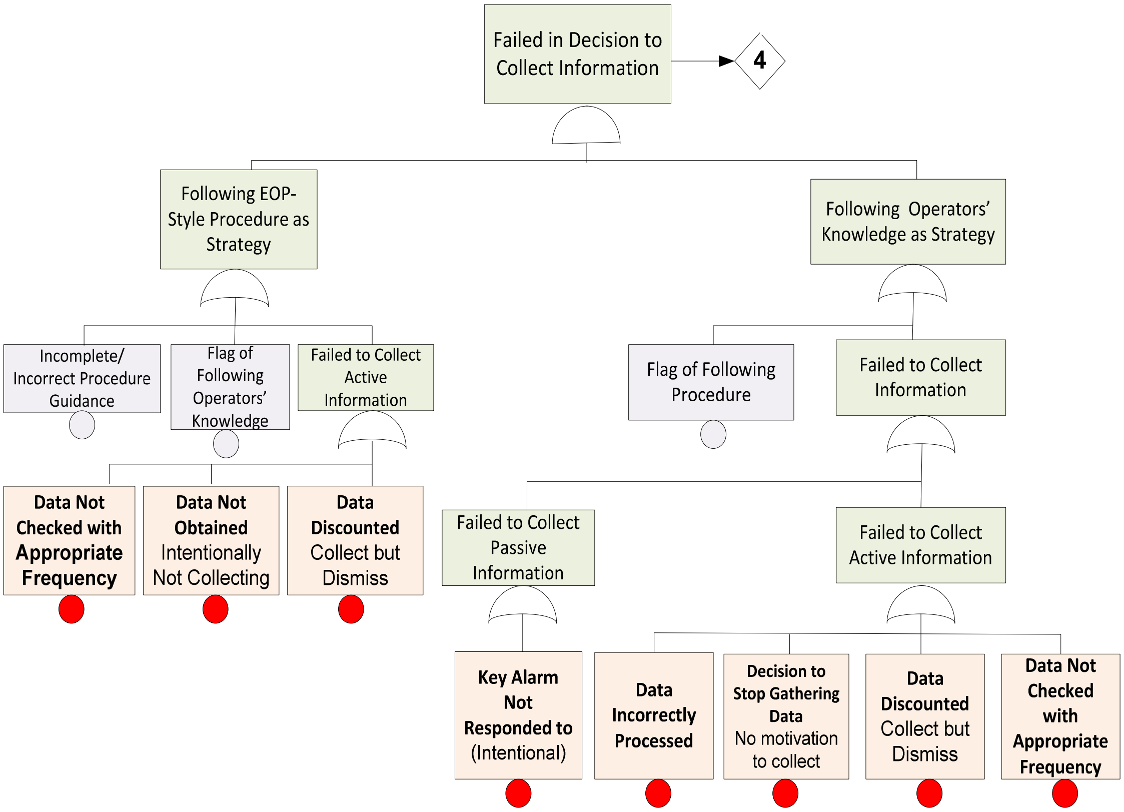


Figure 6-3: The Failure in Decision to Collect Information part of the Fault Tree

6.1.2 Failure in Execution to Collect Information

According to Figure 6-2, the crew may fail to collect either primary or secondary information because of their failure in execution to collect information . This could occur because they failed to collect either passive or active information. The CFM representing the manner in which failure to collect passive information could occur is **Key Alarm Not Responded to (i.e. unintentionally)** while those representing the manner in which failure to collect active information could occur include **Data Not Checked with Appropriate Frequency, Wrong Data Source Attended to**, and **Reading Error.**

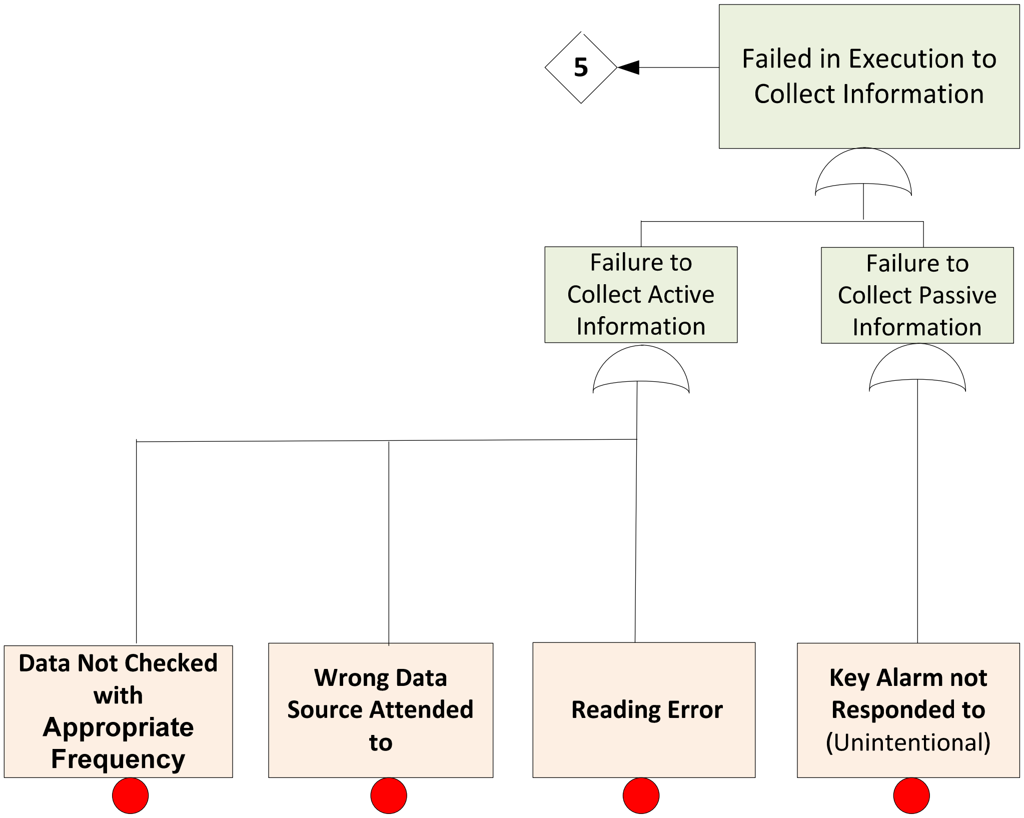


Figure 6-4: The Failure in Execution to Collect Information part of the Fault Tree

6.2 *Failure in Making the Correct Decision Given Necessary Information*

While following procedure or relying on their knowledge, the crew could fail in making the correct decision even if they have already collected the necessary information needed (Figure 6-5). In the procedure mode, this wrong decision could manifest in the form of the CFMs, **Procedure Misinterpreted** and **Procedure Step Omitted (i.e. intentional)** or when they deviate from the procedure being used. The crew's deviation from the procedure being used would manifest in the form of the CFM, **Inappropriate Transfer to a Different Procedure,** error in action decision or situational assessment. While relying on their knowledge, the crew could fail solving problem and making decisions due to error in action decision or situational assessment. The CFMs representing the error in action decision include **Inappropriate Strategy Chosen** and **Decision to Delay Action** while those representing error in situational assessment include **Plant / System State Misdiagnosed** and **Failure to Adapt Procedure to the Situation**.

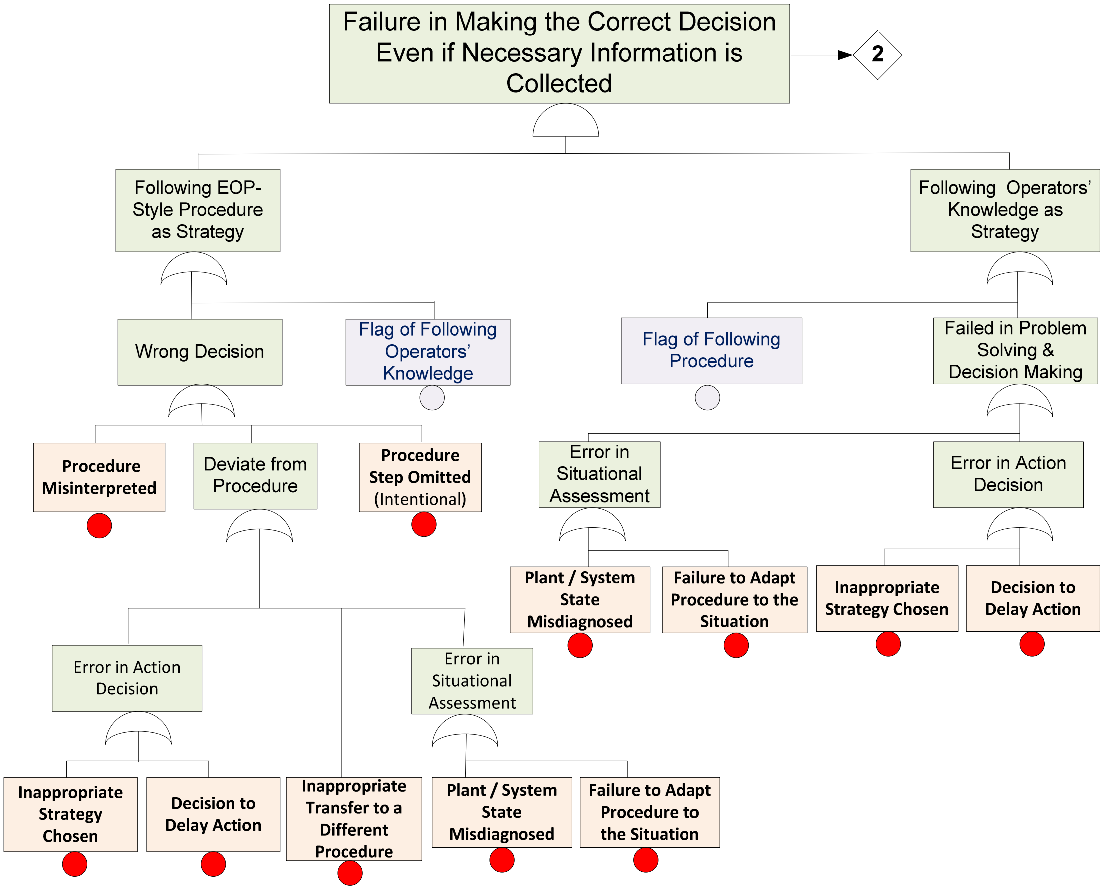


Figure 6-5: Failure in Making the Correct Decision part of the Fault Tree

6.3 *Failure in Taking the Correct Action Given Correct Decision*

The manner in which the failures in this part of the simplified cognitive model occur is represented by the following CFMs: **Action on Wrong Component / Object**, **Incorrect Timing** and **Incorrect Operation of Component / Object**.

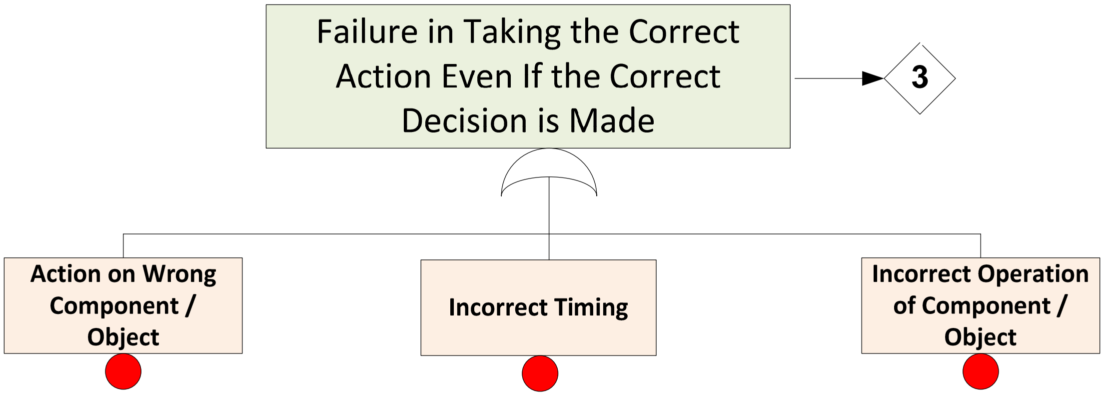


Figure 6-6: Failure in Taking the Correct Action part of the Fault Tree

The expected output from using the FTs is the list of CFMs relevant to each CRT branch point, hence HFE, while the inputs needed to aid in its application include the HFE definition, crew and plant context, identified safety function, developed CRT and identified critical paths in the CRT [25].

The use of these FTs which are developed as a template in order to satisfy all the possible HFEs and crew plant interaction scenarios may result in a very large and complex model. Therefore, the analyst may adhere to the following principles (depending on the specific context of interest) in order to make the process more practical [25]:

- Use the nature of the branch point to identify the relevant part of the CFM FT. For example, if a branch point corresponds to the crew transferring to a specific procedure, then the “information” and “decision” errors are dominant and the “action” error may be ignored.
- Determine the status of the flags in the FT. If the status of a flag is off, then the related section of the FT may be completely ignored. For example if in a branch point the crew is relying on their knowledge instead of following procedure, then

the “Flag of Following Procedure” should be set to “off” eliminating the “Following EOP Style Procedure as Strategy” section of the FT.

7 Crew Failure Modes

Crew failures modes (CFMs) are used to further specify the possible forms of failure in each of the Information, Decision and Action (IDA) phases (i.e. they represent the manner in which failures occur in each IDA phase). They are the generic functional modes of failure of the crew in its interactions with the plant and represent the manifestation of the crew failure mechanisms and proximate causes of failure. They are selected to cover the various modes of crew response including procedure driven, (PD), knowledge driven (KD), or a hybrid of both (HD). In the PD mode, CFMs are selected to represent how the subtasks typically found in operating procedures in nuclear power plants can be viewed by an observer who has an understanding of the crew's expected response to a particular emergency situation. In order to avoid double counting crew failure scenarios during the estimation of human error probabilities (HEPs), the CFMs are defined as being mutually exclusive or orthogonal. Note that "orthogonal" refers to how the CFMs are defined (eliminating overlap in their definitions) and should not be confused with mathematical orthogonality.

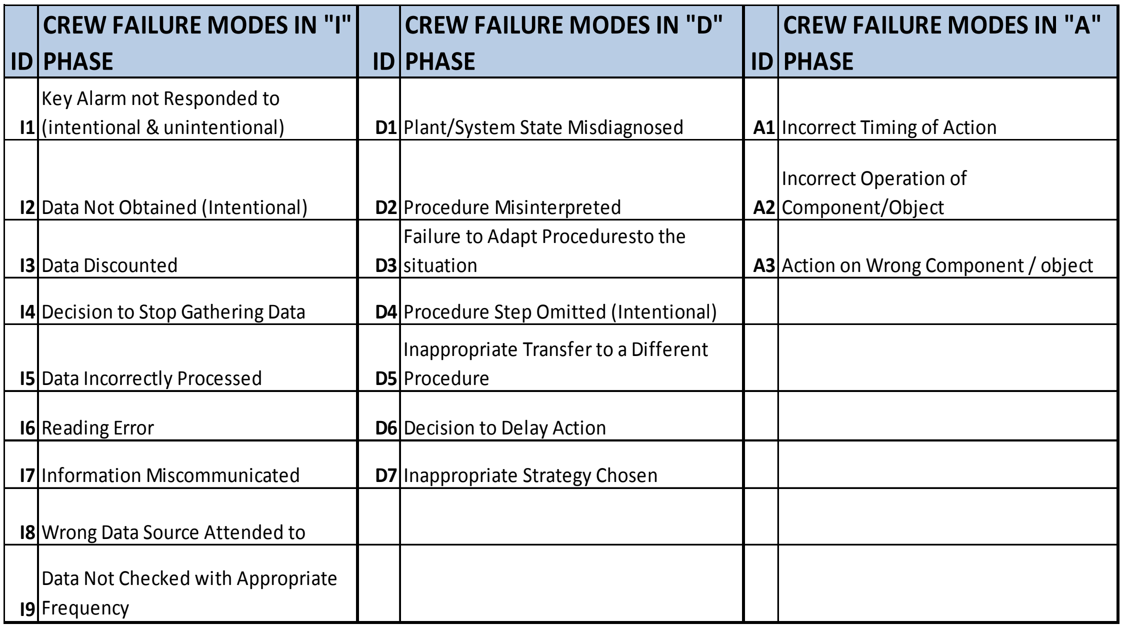
7.1 Development of the CFM Set and Hierarchy

Initially, we developed a set of CFMs based on aggregated information from nuclear industry operating experience, relevant literature on crew error modes in nuclear power plants (NPPs) and discussions with NPP operators and experts. This was an iterative process which was repeated several times until we obtained a fairly representative set of CFMs. Thereafter, we integrated the error modes defined in the

US Nuclear regulatory commission's (NRC's) Scenario Authoring, Characterization, and Debriefing Application (SACADA) database project [30] into our initial CFM to obtain our proposed CFM set and hierarchy. The SACADA database project which is a part of the US NRC's HRA data program [31] is an on-going data collection effort sponsored by the US NRC and aimed at collecting human performance data / information for use in human reliability application. This database is being developed by a team of well qualified industry experts from all parts of the world with a wealth of relevant experience to address the lack of appropriate and sufficient human performance data that is currently affecting human error probability (HEP) estimation in particular and the overall HRA quality in general. Hence, we incorporated the error modes from this database so that it will provide the necessary statistical basis needed by our methodology when the database matures in the future.

Table 7-1 shows the set of CFMs. Each CFM is defined based on the particular I-D-A phase in which it occurs. 19 main CFMs have been defined (9 in the "I" phase, 7 in the "D" phase and 3 in the "A" phase). Since we plan to incorporate data from the SACADA database project into our methodology, we have added a hierarchical structure to the CFMs (Table 7-2) to enable us maximize the use of its data points when they becomes available. Note that the main CFMs are indicated in green with the ID numbers while the lower level elements are indicated in other colors. Table 7-3 shows how the error modes from the SACADA project map to the main CFMs in our methodology.

Table 7-1: Set of CFMs



ID	CREW FAILURE MODES IN "I" PHASE	ID	CREW FAILURE MODES IN "D" PHASE	ID	CREW FAILURE MODES IN "A" PHASE
I1	Key Alarm not Responded to (intentional & unintentional)	D1	Plant/System State Misdiagnosed	A1	Incorrect Timing of Action
I2	Data Not Obtained (Intentional)	D2	Procedure Misinterpreted	A2	Incorrect Operation of Component/Object
I3	Data Discounted	D3	Failure to Adapt Proceduresto the situation	A3	Action on Wrong Component / object
I4	Decision to Stop Gathering Data	D4	Procedure Step Omitted (Intentional)		
I5	Data Incorrectly Processed	D5	Inappropriate Transfer to a Different Procedure		
I6	Reading Error	D6	Decision to Delay Action		
I7	Information Miscommunicated	D7	Inappropriate Strategy Chosen		
I8	Wrong Data Source Attended to				
I9	Data Not Checked with Appropriate Frequency				

7.2 CFMs in the Information Gathering / Processing "I" Phase

The errors within the "I" phase assume that the crew has failed in detecting, noticing and understanding the plant function(s) they are supposed to be handling. Failure in this phase can be divided into two major groups namely: failure to collect passive information and failure to collect active information. The CFM that would occur during passive information gathering (i.e. when the information to be collected is unexpected) is "Key Alarm Not Responded To". Other CFMs occur during active information gathering (when crew is directed or told to get the information).

Table 7-2: Hierarchical structure of CFM set

ID	CREW FAILURE MODES IN "I" PHASE	ID	CREW FAILURE MODES IN "D" PHASE	ID	CREW FAILURE MODES IN "A" PHASE
I1	**Key Alarm not Responded to (intentional & unintentional)**	D1	**Plant/System State Misdiagnosed**	A1	**Incorrect Timing of Action**
	Not detected		Lack of awareness of plant condition		Premature /delayed action
	Not noticed		Failure to form a correct understanding or revise initial false concept		Forget to take the required actions
	Not understood	D2	**Procedure Misinterpreted**	A2	**Incorrect Operation of Component/Object**
I2	**Data Not Obtained (Intentional)**		Difficulty following or using procedure		Executed discrete actions incorrectly
I3	**Data Discounted**	D3	**Failure to Adapt Procedures to the situation**		Place a component in the wrong position
I4	**Decision to Stop Gathering Data**		Failed to take proactive action / anticipate required action		Skipped one or more action steps
15	**Data Incorrectly Processed**		Failed to re-evaluate / revise response as situation changed		Performed actions in wrong order
	data misinterpreted		Failed to correctly balance competing priorities		Failed to perform prerequisite actions of the primary actions
	Slow interpretation of plant parameters	D4	**Procedure Step Omitted (Intentional)**		Dynamic manual control problem
16	**Reading Error**		Skip Procedure Step	A3	**Action on Wrong Component / object**
	Procedure Reading Error		Postpone Procedure Step		
	Skip procedure step (unintentional)	D5	**Inappropriate Transfer to a Different Procedure**		
	Indicator Reading Error		Available procedure not consulted		
	Key parameter not detected		Incorrect transfer to another procedure		
I7	**Information Miscommunicated**		Use of the wrong procedure		
	Missed or incorrect communication by the sender		Violating general procedure usage rules		
	Missed communication of critical data	D6	**Decision to Delay Action**		
	Incorrect communication		Decide to Wait for More Information		
	wrong information		Delayed making decision		
	Incomplete information	D7	**Inappropriate Strategy Chosen**		
	Imprecise information		Failed to consider all options		
	Ambiguous information		Made incorrect choice		
	Communication Standards deficiencies				
	Not directed to the right person				
	Wrong format				
	Poor timing				
	Receiver misunderstanding of information				
	Misunderstood and did not repeat back				
	Repeat back and uncorrected by sender				
I8	**Wrong Data Source Attended to**				
19	**Data Not Checked with Appropriate Frequency**				

Table 7-3: SACADA Error Modes mapped to our CFMs

LIST OF CFMS	ERROR MODES FROM SCADA DATABASE	LIST OF CFMS	ERROR MODES FROM SCADA DATABASE
Information Miscommunicated	□ **Sender error**: Missed or incorrect communication by the sender	Procedure Misinterpreted	○ **Misinterpreted**: Misinterpreted procedure instruction.
	• **Missed communication**: critical information not communicated.		• **Following Problem**: Trouble following or using procedure
	• **Incorrect communication**	Failure to Adapt Procedures to the Situation	• **Not Adapted**: Failed to adapt to the situation.
	○ **Wrong information**.		○ **Proactive**: Failed to take proactive action/anticipate required actions.
	○ **Incomplete information.**		○ **Adapt**: Failed to adapt procedures to the situation.
	○ **Imprecise information**.		○ **Re-evaluate**: Failed to re-evaluate/revise response as situation changed.
	○ **Ambiguous information**: unspecific in communication content.		○ **Prioritize**: Failed to correctly balance competing priorities.
	• **Communication standards deficiencies**	Procedure Step Omitted (Intentional)	○ **Specific/Focused Error**: Misinterpreted, omitted or incorrectly performed one or more substep of a single step.
	○ **Poorly directed**: Not directed to the right person.	Inappropriate Transfer to a Different Procedure	• **Not Consulted**: Failed to consult available procedure.
	○ **Wrong format**: Phonetics/clear terms were not used appropriately.		○ **Wrong**: Used or transferred to a wrong procedure.
	○ **Poor timing**: Too early or too late.		○ **Deviated**: Incorrectly decided to deviate from the correct procedure
	□ **Receiver misunderstanding**		○ **Usage Rules**: Violating general usage rules. (explain):_______________
	• **No repeat back**: misunderstood and did not repeat back	Inappropriate Strategy Chosen	• **Comprehensive**: Failed to consider all options.
	• **Repeat back and uncorrected by sender**		• **Choice**: Made incorrect choice.
Data Not Obtained (Intentional)		Decision to Delay Action	• **Delayed**: Delayed making decision.
Data Discounted	▪ **Discredited**: critical data dismissed, discredited or discounted	Incorrect Timing of Action	o **Action not taken**: Forget to take required actions.
Key Alarm Not Responded to	▪ **Alarm Issues**: Key alarms not detected or not responded to.	Incorrect Operation of Component / Object	o **Executed discrete action(s) incorrectly**
Decision to Stop Gathering Data			• **Wrong position**.
Data Incorrectly Processed	▪ **Misinterpreted**: critical data misinterpreted		• **Skip**: Skipped one or more steps
	▪ **Slow**: Slow interpretation of plant parameters		• **Order**: Actions were performed in a wrong order
Reading Error	▪ **Indicator Issues**: Key parameter value not detected or incorrectly read		• **State Error**: Failed to perform prerequisite actions of the primary actions.
Wrong Data Source Attended to			o **Dynamic Manual Control**: Dynamic manual control problem.
Data Not Checked with Appropriate Frequency		Action on Wrong Component / Object	• **Wrong object**.
Plant / System State Misdiagnosed	▪ **Incorrect/Incomplete**: Failure to form a correct understanding or revise initial false concept.		
	▪ **Awareness**: lack of awareness of plant conditions		

7.2.1 Key Alarm Not Responded To

This is a case where the crew intentionally or unintentionally fails to respond to a key alarm. A key alarm is one for which response is expected to be immediate and the crew is adequately trained. It includes failure to detect, notice or understand the alarm. It is assumed that the alarm is the most important cue that is adequate for a correct assessment of the plant condition, and the expected response should lead to a successful outcome. A key alarm is typically expected to initiate an immediate response which may include working through a procedure. This CFM also includes not perceiving, dismissing and misperceiving the key alarm. For example, the crew may receive an alarm, but may be busy carrying out some other task which they believe is more important than responding to the alarm. Hence, they intentionally ignore it. Also, they may not receive the alarm because of the man-machine interface, noisy environment, or high work load and therefore, they don't respond to it unintentionally.

7.2.2 Data Not Obtained (Intentional)

This CFM is applicable to a situation where the crew intentionally fails to collect data. This implies that the need for data is understood but a conscious decision has been made not to collect it. This may be because the crew has determined that the data is incorrect, misleading or unsuitable for the intended purpose. It may also be because they already have similar data which they believe should suffice. As an example, the crew may need to obtain specific data which they just obtained a few minutes earlier. Therefore, they make a decision not to check the data again when requested.

7.2.3 Data Discounted

This is a situation where the crew understands the need for and has obtained correct information (either personally or communicated by another crew member) but decides to discard it (i.e. there is no intent to use or include it in the assessment of the plant state). In this case, the data is first gathered and later discounted as opposed to the CFM “Data Not Obtained” where the information has not been gathered at all. For example, the crew may obtain some information initially but on a second thought, they may decide to give it up because they assume it is not relevant to the current situation they are encountering.

7.2.4 Decision to Stop Gathering Data

This is a situation where the crew has been collecting information and at some point determines that they do not require any more data based on their confidence in the assessment of the plant status (i.e. they have collected enough information to enable them obtain a true picture of the plant state and no additional data is needed). Hence, there is no motivation to continue the data collection process since the goal has been accomplished. As an example, the crew may be gathering data with regards to a certain situation in the plant. They get interrupted by other persons or information and thereafter, they decide to stop collecting the data.

7.2.5 Data Incorrectly Processed

This is a situation where the crew misinterprets or is slow in interpreting plant parameters / information read from the indicator or received from other crew members. As an example, during the loss of seal cooling event, a crew member may check the status of the charging pump and conclude that the charging flow is normal because the charging pump is still running. However, the failed (open) release valve may have caused no charging flow to the seals but the crew member may not realize it. He/ she may believe that the charging flow is normal.

7.2.6 Reading Error

This CFM is applicable to a situation where the crew tries to read a procedure or indicator but somehow makes a mistake. It include mistakes in reading procedure steps, detecting and/or reading the values of parameters from some form of display like an indicator, and mistakes in determining the status of equipment based on indications on the control panel. This is a case where everything is put in place correctly but the crew still makes a simple mistake. It is more of an “eye” error. For example, during an upset plant condition, the crew may misread a procedure step “turn valve A 3 times clockwise” as “turn valve A 2 times clockwise”, an “on” indicator pump light for “off” or a “closed” valve indicator for “open”.

7.2.7 Data Miscommunicated

This covers the case where there is a missed or incorrect transfer of information between crew members (i.e. the receiver and sender). The sender may not communicate the necessary information or may pass along incorrect information in the form of wrong, incomplete, imprecise or ambiguous information to the receiver. Also, the crew member may direct the information to the wrong person, present it in the wrong format (e.g. inappropriate use of terms or phonetics) or at the wrong time (i.e. either too early or too late). The receiver may mishear or misunderstand the information transmitted and does not repeat back to the sender (for an opportunity for confirmation). Also, the crew member may repeat the misunderstood information to the sender but the sender does not correct it. As an example, during a plant upset condition, the control room crew may not pass on the required information to the field crew on time. This may cause a delay in returning the plant to a stable state.

7.2.8 Wrong Data Source Attended to

This is a situation where the crew is aware of the need to obtain information and the correct information is available, but they unintentionally try to collect this information from the wrong source. For example, the required reading should be obtained from indicator "A" but it was obtained from "B".

7.2.9 Data Not Checked With Appropriate Frequency

This is the case where the crew is not adequately implementing the monitoring strategy for data collection. For example, the crew may have the task of monitoring a parameter and the instruction to initiate some kind of response is dependent on a critical value of that parameter whose value is changing and is expected to keep changing rather than remain static. They may miss checking this critical parameter value and hence, fail to initiate the expected response in a timely manner.

7.3 CFMs in the Situation Assessment / Decision Making "D" Phase

The errors within the "D" phase assume that there is failure in situation assessment, problem solving and decision making "D" given correct information gathering "I". Therefore, the assumption is made that the crew has detected, noticed and understood the plant function(s) they are supposed to be handling. However, they have failed to make a correct assessment of the plant condition(s), diagnose, decide and plan the adequate response needed to solve the problem at hand. Failures in this phase result in implementing an incorrect strategy or approach and hence failing the required function. It is assumed that the CFMs in this phase occur as a result of the crew's intent (i.e. they are intentional errors).

7.3.1 Plant / System State Misdiagnosed

This CFM applies to a situation where the crew conducts a wrong assessment of the plant condition. This may be because of their lack of awareness of the current condition of the plant, incorrect understanding of the plant condition or failure to revise their initial concept of the plant condition (which was false). As an example, during a steam generator tube rupture (SGTR) event, the crew may notice that the steam generator (SG) is almost solid and decide to trip the auxiliary feed water (AFW) pumps when they should not.

7.3.2 Procedure Misinterpreted

This applies to the situation where a procedure is incorrectly understood and, a decision is made based on the crew's misinterpretation, leading to an incorrect response to the current plant condition. It is also applicable to a situation where the crew has difficulty in following or using the procedure. This may be due to reasons such as the complex nature of the procedure logic, the ambiguity of the procedure steps, or the complicated structure of the procedure. As an example, the crew did not understand some of the steps in the procedure they were using while restoring a pumping system. This led to a complete shutdown of the pumping system and other auxiliary systems that it supports.

7.3.3 Failure to Adapt Procedures to the Situation

This is applicable to a situation where the crew fails to adapt procedures to the situation at hand. It also covers cases where they fail to take proactive action, anticipate the required actions, re-evaluate or revise their response as the situation changes, or correctly balance competing priorities. This may be due to the ambiguity of the procedure or lack of understanding of the procedure as it applies to the particular situation. For example, the crew did not revise their response due to a changing situation, hence they kept following the initial procedure which was no longer applicable at that point in time.

7.3.4 Procedure Step Omitted (Intentional)

This is the case where the crew is working through a procedure and they skip or postpone a step or sub-step. When the crew skips a step, it implies that the crew has decided to rely on their knowledge, (i.e., mental reasoning) instead of following the procedure step by step. Hence they have no intention of completing it. This could be due to their lack of confidence in the procedure or the belief that skipping the step will still lead them to the expected result; thereby saving them some time which could be used to carry out other task. When they postpone a step, there is an intent or plan to complete it at a later time. The crew may decide to postpone the procedure step because they believe that doing so will still lead them to the expected outcome while spending less time on the entire procedure. Also, they may have something more important to do and they skip the step with the intent of returning to it later while believing that the expected response will still be achieved. As an example, while performing a task, the crew omitted a procedure step because they believed it wasn't relevant.

7.3.5 Inappropriate Transfer to a Different Procedure

This is the situation where the crew is working through a procedure and then decide to transfer to another one when they are not supposed to do so. The decision to transfer to another procedure may be because the crew assumes that it will save them more time while obtaining the same response they would have had from following the initial procedure. However, this is an incorrect transfer to another procedure and it may result in an unsuccessful response. This CFM also covers the violation of general procedure rules, situations where the correct procedure is available but the crew doesn’t consult it and also when the wrong procedure is used. For example, while completing a task, the crew transferred to another procedure when the current procedure they were using did not call for a transfer.

7.3.6 Decision to Delay Action

This is applicable to the situation where the crew having conducted a correct assessment of the plant state, decide not to implement the action or delay making decision (because they are waiting for more information) to the extent that the response is unsuccessful even when it is finally completed. As an example, during the loss of heat sink event, the crew may postpone the required feed and bleed operation, even when the criteria to perform it had been met.

7.3.7 Inappropriate Strategy Chosen

This is the case where the crew having made a correct assessment of the plant condition, decide to take a different course of action from the expected “normal” one (i.e. they made an incorrect choice). It is assumed that the expected or normal course of action is the guaranteed success path and that the alternate action may result in success or failure depending on the context. The crew’s decision to choose an alternate path may be as a result of their failure to consider all options, familiarity with the chosen path or lack of clarity of the expected course of action. For example, when the crew notices that the safety injection system (SIS) set point is about to be met and they do not find any significant event such as loss of coolant accident (LOCA) or steam generator tube rupture (SGTR), they may manually bypass the SIS (which is not an appropriate strategy at this point) to minimize the consequence due to the occurrence of safety injection (SI).

7.4 CFMs in the Action Execution “A” Phase

The errors within the “A” phase assume that there is failure in action execution “A” given correct situation assessment, problem solving and decision making “D” and correct information gathering “I”. Therefore, the assumption is made that the crew has detected, noticed and understood the plant function(s) they are supposed to be handling. Also, they have made a correct assessment of the plant condition(s), diagnosed, decided and planned the adequate response needed to solve the problem. However, they fail in executing the response or required action. It is assumed that the CFMs in this phase are unintentional errors. This phase mainly consist of noncognitive errors of slips and lapses even though, some cognitive errors may appear in some instances.

7.4.1 Incorrect Timing of Action

This applies to the situation where the crew is in the process of performing an action and they complete it prematurely, spend too much time on it or forget to take the required actions. It is an honest delay on the crew's part and not a deliberate attempt to slow down the desired action. As an example, the crew may be in the process of starting a pump and they become distracted by an alarm or a call to attend to another issue. They may return to complete the pump start-up or may totally forget altogether.

7.4.2 Incorrect Operation of Component / Object

This is a case where the right component or object is selected but it is manipulated or controlled wrongly. It includes performing actions out of sequence (e.g. skipping operation steps or reversing steps in the action when the ordering matters), and the placement of a component in the wrong position. This CFM also includes the failure to use alternative actions in instances when a change in situation has made it almost impossible to perform the original action, and dynamic manual control problems. In all these instances, the component is not operated properly and it may lead to inaccurate results being obtained. For example, while trying to close a valve, the crew turned the wheel 5 times in the clockwise direction while they were supposed to turn it 5 times in the anti-clockwise direction.

7.4.3 Action on Wrong Component / Object

This CFM covers a situation where the wrong component or system is chosen to be manipulated, implying that the intent is to perform the right action however; it is carried out on the wrong component. For example, the crew was supposed to start pump A but mistakenly started pump B.

8 Performance Influencing Factors

System failures have become more complicated due to the increasing complexity of systems that are being developed. This has led to more human-system interactions and has made it necessary to find ways of describing and representing different aspects of these interactions. Hence, performance influencing factors (PIFs) also known as performance shaping factors (PSFs) have been adopted by many HRA methods for the aforementioned purpose. PIFs are the contextual factors that affect human performance by enhancing or degrading it. Under different situations, they are used to simplify the contexts and causes affecting human performance. PIFs have different uses in HRA which include; representation of different factors influencing individual or team behaviors, decision making and actions, description of different aspects of human-system interactions, adjustment of HEP depending on the situation, prediction of common conditions that lead to certain types of error, indication of positive or negative influences on human performance, identification of roots causes of error and subsequent areas for improvement.

The state of a PIF (i.e. its level of influence) is defined on different scales and this is dependent on the HRA method of choice. This level of influence typically ranges from low to high, in predetermined increments and it's used to modify HEP by increasing or reducing the likelihood of human error. Depending on the PIF, its state can be accessed by direct observation / measurement or by extrapolation from behavioral indicators or other observable metrics.

8.1 Issues with PIF sets used in current HRA methods

Presently, no standard set of PIFs have been adopted for use by HRA methods. Each HRA method uses a different set of PIF for its HEP quantification, many of which have overlapping definitions. While most of these PIF sets have some roots in human performance literature, they are not suitable for use in developing a causal model. This is because they were only designed to be assessed by experts and not for model quantification. When the assessments of PIFs are done by experts, they can mentally compensate for the overlapping definitions, whereas using the same PIFs in a model requires the analyst to remove the overlap or explicitly capture the mental adjustment [32]. Also, some of the available PIF sets do not contain adequate information to cover the different aspects of human-system interaction while others lack a differentiation between factors that influence performance and behaviors that are used to indicate the state of these performance factors. For example, the PIF "work process" which is part of some PIF sets [19], often includes specific behaviors that do not indicate the true state of the PIF.

8.2 Development of the Grouping and Hierarchy

We began the process of developing our PIF grouping and hierarchy with a set of PIFs that was proposed by K. M. Groth [32], [33]. Groth's PIF set was selected for the following reasons:

- It is comprehensive set that was developed by aggregating information from most PIF sets used in a number of HRA methods including IDAC [34], SPAR-H [19], CREAM [12], HEART [35], [36], THERP [7]. It also incorporates the PIFs from US NRC's Good Practice for HRA [16].

- The PIF taxonomies of IDAC [34], which is the team-centered version of the human response model (IDA) [22] adopted for use in this research work, included PIFs from several HRA methods. The Human Event Repository and Analysis (HERA) [37], [38] database was also reviewed and relevant PIFs were mapped into this set.
- It has a hierarchical structure which captures information about natural interdependencies among the PIFs. It can be expanded and collapsed as needed therefore promoting its use for both quantitative and qualitative analysis.
- It is orthogonally defined meaning that the PIFs have no overlap in their definition even though they may be related. This reduces the artificial dependencies that are created due to overlapping definitions.
- It is also neutrally defined enabling each PIF to have a positive or negative impact on human performance depending on the situation in context.

In Groth's PIF set, there are five main categories namely: Organization-based, Team-based, Person-based, Machine-based, and Situation/Stressor-based [33]. See Table A1 for the complete list of the PIFs and also [32], [33] for the complete definition of each PIF and the categories.

Even though Groth's PIF set was developed by aggregating information from other PIF sets used in HRA and this included IDAC [34], we had to specifically review and also incorporate some features of the PIFs from the IDAC model into our PIF grouping and hierarchy because:

- It is the team-centered version of the cognitive model (IDA) adopted for use in our HRA methodology, allowing us to take advantage of the extensive research work that has been done to develop it.
- It offers a hierarchical structure and logical flow of information which is necessary for the development of a directed model.
- Its PIFs are also orthogonally defined and the model offers qualitative links between its PIFs, which would also aid in the development of a directed model.
- It is specifically focused on operating crews which is also the focus of our HRA methodology.

After incorporating features of the PIFs from IDAC, we also made sure that our PIF set met the necessary requirements indicated in the US NRC’s Good Practice for HRA [16] and can be modified to interface with existing HRA methods like SPAR-H [19] which is most widely used for HRA by HRA practitioners in US nuclear power plants.

Thereafter, we incorporated the error causes defined in the US Nuclear regulatory commission’s (NRC’s) Scenario Authoring, Characterization, and Debriefing Application (SACADA) database project into our PIF groupings and hierarchy. As has been discussed earlier under the section (Development of the CFM Set and Hierarchy), this database project is an on-going data collection effort sponsored by the US NRC and is aimed at collecting human performance data / information for use in human reliability application. Hence, we incorporated these error causes so that it will provide the necessary statistical basis needed by our methodology when the database matures in the future.

Our final PIF set which is used for causal modeling was developed by aggregating the information from these PIF sets and then we refined them into a single comprehensive set and structure hierarchy. Table A2 illustrates how the PIFs used in current HRA map onto the new PIF grouping. It specifically shows how the PIFs from the Good Practices for HRA, Groth's PIF set, PIFs from IDAC model and SPAR-H map to the PIFs in our proposed grouping and hierarchy. In Table A3, we show how the error causes from the SACADA project map to the PIFs in our methodology.

8.3 PIF Grouping and Hierarchy

Although Groth's PIF set has several advantages for inclusion in a causal model based framework as previously discussed, we have to make modifications and changes to its structure before using it in our work. This is because Groth's PIFs were grouped in terms of their nature and the responsible parties (for example her organization-based PIFs are those PIFs that the organization is primarily responsible for) while this research focuses on the impact of PIFs on the crew's performance. Also, even though the IDAC model focuses on operating crews, its PIFs are categorized in terms of factors that are either internal or external to the crew as opposed to how they impact crew's performance. Therefore, our final PIF set which is used for causal modeling was developed by aggregating the information from these sources. Thereafter, we reorganized and grouped them in terms of their impact on the crew's performance and this form the basis of this set.

When an abnormal event (problem) occurs in the plant, the crew starts the process of trying to solve the problem (safely stabilizing the plant) by responding cognitively, emotionally and physically [40]. These three types of responses are interdependent and they form the crew's response spectrum which is model by IDA (the human response model). So, in order to determine the impact of the PIFs on the crew's performance, it is necessary to organize the PIFs in terms of the crew's natural response spectrum. The PIFs have been organized into nine (9) main groups in an attempt to look at the frontline factors that directly affect / impact human performance. Note that these groups are also individually considered as PIFs. The groups (also known as the "Primary or level 1 PIFs") are Knowledge/Abilities and Bias which maps to cognitive response, Stress maps to emotional response, while Procedures, Resources, Team Effectiveness, Human System Interface (HSI), Task Load, and Time Constraint all maps to physical world (Figure 8-1).

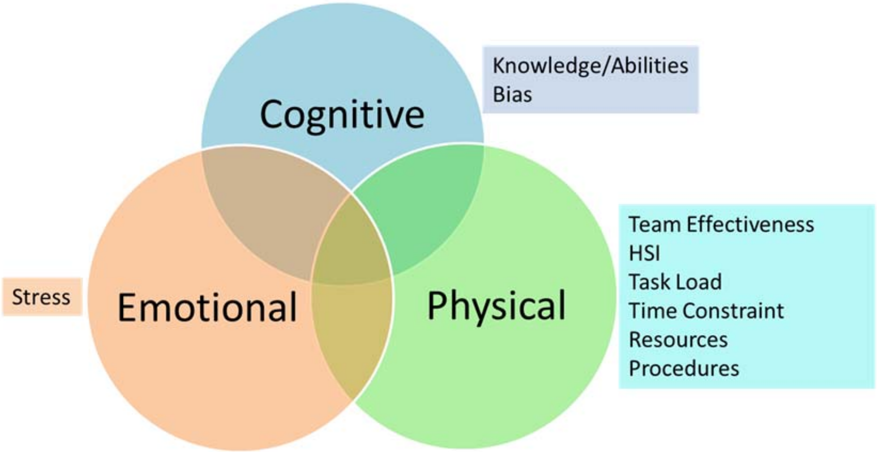


Figure 8-1: Crew's response spectrum & Primary PIF groups

The PIFs are classified into levels within the groups, hence forming a hierarchical structure which can be fully expanded for use in qualitative analysis and collapsed for use in quantitative analysis (Table 8-1). They are organized to show the beginning of a causal model. The main idea is to pick limited groups of PIFs to serve as frontline factors which affect human performance from a causal perspective. These PIF groups are orthogonally defined in a sense, meaning that we have attempted to reduce the overlap in their definitions (but not totally) even though the groups may be related to each other. Level 1 PIFs which are also the main or Primary PIF groups have a directly impact on human performance. Level 2 PIFs either directly affect or form parts of (make up) the level 1 PIFs and the same applies to the level 3 PIFs.

Table 8-1: Proposed PIF Groups and Hierarchy

PROPOSED PIF GROUPS & HIERARCHY								
HSI	**Procedures**	**Resources**	**Team Effectiveness**	**Knowledge/Abilities**	**Bias**	**Stress**	**Task Load**	**Time Constraint**
HSI Input	Procedure Quality	Tools	Communication	Knowledge/Experience/Skill (Content)	Morale/Motivation/Attitude	Stress due to Situation Perception	Cognitive Complexity	Time Constraint
HSI Output	Procedure Availability	Tool Availability	Communication Quality	Task Training	Safety Culture	Perceived Situation Urgency	Inherent Cognitive Complexity	
		Tool Quality	Communication Availability	Knowledge/Experience/Skill (Access)	Confidence in Information	Perceived Situation Severity	Cognitive Complexity due to External factors	
		Work Place Adequacy	Team Coordination	Attention	Familarity with or Recency of Situation	Stress due to Decision	Execution Complexity	
			Leadership	Physical Abilities and Readiness	Competing or Conflicting Goals		Inherent Execution Complexity	
			Team Cohesion				Execution Complexity due to External fctors	
			Role Awareness				Extra Work Load	
			Team Composition				Passive Information Load	
			Team Training					

KEY	**MEANING**
🟦	Level 1 PIFs
🟥	Level 2 PIFs
🟫	Level 3 PIFs

8.4 Definitions of the proposed PIFs

Our proposed PIF set has been structured to enable its use in both qualitative and quantitative HRA applications. It may not be possible to directly include all the PIFs in the hierarchical structure in a quantitative analysis. However, the hierarchical structure provides the flexibility to use the same PIF set in applications where every factor can be explicitly identified (e.g. computer modeling) and also where only the high level factors are required (may be due to lack of data to support the lower level factors) as is the case with many HRA methods (where error analysis and HEP estimation is done manually or with the aid of a tool). In this methodology, the idea is to use the level 2 and 3 PIFs to aid the analyst in the assessment of the frontline (nine primary PIFs).

In the definition of the PIFs, three aspects are considered which include:

- Its nature (i.e. its inborn or inherent qualities). For example, procedures will always be written set of step-by-step instructions that a crew would follow to complete a task.
- Various attributes of the PIF (i.e. characteristics or qualities associated with or used to describe it). In other words, this is how we see or measure the PIF (e.g. is the procedure adequate, inadequate, etc).
- Its influence on other PIFs and / or performance (i.e. how it affects or impacts other PIFs or human performance). For example, if the procedure to shut down the reactor is not available when needed, the crew’s stress level due to their perception of the severity of the situation (another PIF) will increase and they

may not be able to correctly shutdown the reactor (their performance is affected and it may lead to error on their part).

8.4.1 Human System Interface (HSI) Group

HSI refers to the ways and means of interaction between the crew and the system. This PIF covers the quality (usability, ergonomics, physical access, etc) of the HSI [41] both in terms of system output as well as the crew's input to the system. This group is made up of two level 2 PIFs namely: HSI Input and HSI Output.

1.1.1.1 Human System Interface (HSI) Input

This PIF refers to quality of HSI with respect to the input provided by the crew. Humans interact with the system by providing input in such ways as turning a dial, pushing a button or entering a command on a keyboard. HSI should be designed to maximize the ability of the human to provide correct input to the system.

1.1.1.2 Human System Interface (HSI) Output

This PIF refers to the quality of the HSI with respect to the information and other outputs generated by the system for use by the crew. Humans interact with the system to get information (system output) which includes reading analog and digital displays [32]. HSI should be designed to maximize the ability of the human to obtain the correct information and feedback from the system. Humans must be able to gain access to the physical location of the output device and clearly read the output. They could be prevented from obtaining the correct output by the presence of inaccurate labels, display ranges, or markings [42], [43]. This PIF would be considered inadequate in situations where there are : inaccurate display formats, label, mimic or display issues with alarms and indicators, spurious alarms, failed alarms, unspecific alarms, misleading indicators, missing indicators, similarity between alarm and indicator controls, nonstandard controls which operate differently from the normal conventions, difficulty in indicator detection due to the occurrence of slight changes, inadequate system feedback like long system response time, inadequate distribution of relevant information over time and space.

8.4.2 Procedures Group

As a PIF, procedures refer to the availability and quality of the explicit step-by-step instructions needed by the crew to perform a task. Ideally, no errors should be committed by the crew when they are following the procedure correctly. However, procedures could be written incorrectly and therefore lead the crew to make errors even with the right intent. This group is made up of two level 2 PIFs namely: Procedure Quality and Procedure Availability.

1.1.1.3 Procedure Quality

Procedure quality refers to the condition of the required procedure with regards to completeness of content, ease of adherence and appropriateness in terms of ensuring adequate job completion. Procedures should be clear, concise, correct, well-written, organized, and adequately formatted [44]. The quality of a procedure would be considered inadequate in instances where it is technically inaccurate and unusable [45]; the format and required level of detail is not appropriate; it provides incomplete and conflicting guidance [43]; its assumptions is not aligned with the actual plant condition; it contains confusable or similar sounding word like decrease and increase.

1.1.1.4 Procedure Availability

This PIF refers to the situation where procedures for the task at hand are in existence and accessible [32]. The procedure should be applicable to the condition which it is intended for. This PIF would be considered inadequate when the required procedure is non-existent, inaccessible, or the available procedure is only partially relevant to the present situation or completely irrelevant.

8.4.3 Resources Group

This refers to the availability and adequacy of the required resources which are necessary to aid the crew in completing their assigned task. Resources are provided by the organization to the crew and these include the two level 2 PIFs (required tools and a conducive work environment).

8.4.3.1 Tools

This PIF refers to the availability and quality of the hardware and software tools (including number and type) that are required to ensure that personnel do not have to develop work-arounds or postpone tasks. Note that tools include both hardware and software packages, and are generally more portable than machinery (which are usually fixed part of a system).As a PIF, tools is comprised of two level 3 PIFs namely Tool Quality and Tool Availability.

8.4.3.1.1 Tool Quality

This PIF refers to the appropriateness [44], [45] and readiness of the required tools. Some tasks require specially designed tools which need to be properly designed, well maintained, and calibrated [34]. In these instances, using general tools instead of the prescribed ones may jeopardize the task and lead to error.

8.4.3.1.2 Tool Availability

As a PIF, Tool Availability refers to the accessibility of the required tools to perform the task at hand. Not having access to the proper tools could lead to the use of inappropriate tools as surrogates or a delay in task completion [7].

8.4.3.2 Work Place Adequacy

This PIF generally refers to the quality of the work environment and includes aspects of workplace layout [12] and configuration [46] that could affect crew performance. For example, poor illumination and constant noise could reduce information perception, and a narrow work space may limit movements and increase the likelihood of introducing unintended actions on the system. In contrast with HSI quality which focuses on fixed equipment (e.g., control room displays) that can't be readily changed by the organization; workplace adequacy covers aspects of the work environment that can be changed by the organization.

8.4.4 Team Effectiveness Group

As a PIF, Team effectiveness refers to the degree of harmonization and synchronization of crew member's contribution to the team's overall goals and team tasks. The team in this context refers to a group of persons working together to achieve a common goal / purpose. In order to work together as a unit, an effective team needs to be properly coordinated and have ability to adequately exchange information between its members. Therefore, Communication and Team Coordination are the two level 2 PIFs in this group.

8.4.4.1 Communication

This PIF refers to the quality of the information exchanged between members of the crew and this could be done verbally or in writing. It also covers the availability of the means and tools necessary for effective communication and allows for the sharing of knowledge about a specific situation between crew members [47]. It is made up of two level 3 PIFs namely: Communication Quality and Communication Availability.

8.4.4.1.1 Communication Quality

This PIF refers to the degree by which the information that is received corresponds to the information that was transmitted [34]. It is affected by a person's inability to articulate the information to be transmitted, clarity of the information transmitted and received, adequacy of the information, external distortion, malfunctioning communication equipment etc.

8.4.4.1.2 Communication Availability

This PIF refers to the existence and accessibility of the tools, means and mechanisms necessary for the crew to share information. In particular when dispersed at different locations, this PIF allows members of the crew to be kept abreast of a shared situation. Untimely communication has the same effect as lack of communication because the information is not communicated when necessary [32].

8.4.4.2 Team Coordination

As a PIF, it refers to the overall ability of a team to work together as a unit to perform a given task [48]. A coordinated team should be cohesive, have the right composition, good leadership, and members should be aware of their roles and responsibilities. Therefore, this PIF is comprised of five level 3 PIFs which include Leadership, Team Cohesion, Role Awareness, Team Composition and Team Training.

8.4.4.2.1 Leadership

This PIF refers to the team leader's ability to set a direction and gain the commitment of the team to change / maintain goals by building relationships and working with them to overcome obstacles to change. The team leader serves as the link between management and the team members. In literature, team leadership (direct supervision) and management are generally referred to as leadership [44], [49], [50]. Here, team leadership has been separated from management because the team leader is considered a team member but with the additional authority and responsibility of setting the direction [51] or goals, assigning tasks to other team members and working with them to accomplish these goals [52].

8.4.4.2.2 Team Cohesion

As a PIF, Team cohesion refers to the interpersonal interaction between the crew members and represents the group morale [34] and attitude towards each other. According to Mullen and Copper [53], facets of team cohesiveness include: interpersonal attraction of the crew members, their commitment to the team task, group pride and team spirit.

8.4.4.2.3 Role Awareness

This PIF represents how well each crew member understands his or her responsibilities, role, and duties within the group. It is influenced by each crew member's formally and informally assigned responsibilities and their interactions with each other [54].

8.4.4.2.4 Team Composition

This PIF refers to the size [50], uniformity and variety of the team which provides the required knowledge, experience and skills to perform a given task [49]. The size is usually determined by the nature of the team task as too small a size creates excessive workload for the team members while too large a size would result in wasted resources, and also a reduction in the overall team performance. The organization is responsible for determining the team composition by staffing [55] the team with personnel that possess the appropriate skill set.

8.4.4.2.5 Team Training

As a PIF, team training refers to the degree to which the crew members are trained on how to work with each other as members of the same team. It is very important to have a crew in which members can collaborate and work effectively together. Hence, one of the ways of achieving this is providing them with the proper training.

8.4.5 Knowledge / Abilities Group

This PIF refers to the adequacy of knowledge and abilities of the crew. In order to perform an assigned task, the crew needs to possess the required knowledge (understanding of the system and task to be performed) [41], [56], experience (accumulation of the knowledge gained over time through training and previous interactions with the system) [57], [58], skill (ability to perform the necessary task related activities with little cognitive effort) [44], the ability to access it when needed, and also the required physical ability. It is difficult to separate knowledge from experience because experience is partly gained by putting the knowledge acquired into practice. However, less experienced personnel are not necessarily less knowledgeable than their more experienced counterparts [32] and vice-versa. As a PIF group, it is comprised of three level 2 PIFs namely: Knowledge/Experience/Skill (content), Knowledge/Experience/Skill (access), and Physical Abilities and Readiness.

8.4.5.1 Knowledge/Experience/Skill (Content)

This PIF refers to the adequacy of knowledge/Experience/skill [45] , [46] that the crew possesses for the task at hand. In addition, the crew needs to form the correct mental model of the situation in order to adequately analyze the problems encountered in the course of performing their assigned tasks. This PIF is comprised of a level 3 PIF referred to as “Task training”.

8.4.5.1.1 Task Training

As a PIF, Task training refers to the degree to which the crew is trained on the specific task so that they would have adequate knowledge/experience/skill to perform it. Training refers to the knowledge and experience imparted to the crew by the organization and it comprises of the course contents, scheduling and frequency of the training courses [32].

8.4.5.2 Knowledge/Experience/Skill (Access)

This PIF refers to the ability to obtain and utilize the Knowledge/Experience/Skill possessed by the crew. In US nuclear power plants, the crew needs to be able to stop, think, act and review (STAR) when challenged with a difficult situation. This PIF is comprised of a level 3 PIF referred to as “Attention”.

8.4.5.2.1 Attention

As a PIF, attention refers to the crew's ability to distribute the available cognitive [32] and physical resources and it can be affected by many external distractions as well as internal thoughts and distractions (e.g. emotional state of mind of each crew member). It is comprised of attention to the current task and attention to the surroundings [34]. Attention to task is the ability of the crew to focus on a task (mainly in interactions with the human-system-interface to monitor and control the system). Attentions to the surroundings involve being aware of the state of the surrounding environment and the actions of other crew members in order to prevent an unintentional change to the system state.

8.4.5.3 Physical Abilities and Readiness

This PIF refers to the crew's physical capability and readiness to perform the task at hand. The crew's physical ability and readiness for duty is affected by the frequency of task assignment, the duration of the task and the particular shift they are assigned to (i.e. day or night shift). Physical Abilities includes alertness [7], [59], fatigue [43], sensory limits, and fitness for duty [45]. Fatigue which also affects this PIF describes the state of being physical weary or worn out. It could affect the crew’s performance by causing errors in skill-based actions, or delayed cognitive responses.

8.4.6 Bias Group

This PIF refers to the crew's tendency to make decisions or reach conclusions based on selected pieces of information while excluding information that doesn’t agree with the decision or conclusion. Bias may appear in the form of confirmation bias, (i.e., only selecting the piece of information that supports one's hypothesis), belief bias, (i.e., only selecting the piece of information that reinforces one's own personal beliefs), and averaging bias (regression toward the mean) [60], [61]. Bias may result from such factors as previous experiences, familiarity with a certain situation specific training, competing goals, and personal motivation, morale and attitude. Bias can also be externally-induced such as preferences or inclinations in judgment encouraged or imposed by the team leader, organizational culture, or a recognized authority. Extreme bias becomes fixation, which could induce systematic errors. As a PIF group, it is comprised of five level 2 PIFs namely: Morale/Motivation/Attitude, Safety Culture, Confidence in Information, Familiarity with or Recency of Situation, and Competing / Conflicting Goals.

8.4.6.1 Morale/Motivation/Attitude (MMA)

Together, this PIF refers to the team's intrinsic characteristics (including personality [49], temperament [62], style [54], strategy, etc.) which indicates their commitment and willingness to thoroughly complete task and the amount of effort they are willing to put into a task. Morale and Motivation [63] reflect the crew member's level of energizing, channeling, and sustaining their effort. Attitude is a positive or negative state of mind or feeling towards the work [41], [59], manifesting itself through such things as the crew member's willingness to voluntarily assist other team mates and take on other duties beyond regularly assigned ones [34].

8.4.6.2 Safety Culture

This PIF refers to the organizational attitude, values, and beliefs toward the employees and the safety of the public [64]. According to the International Atomic Energy Agency (IAEA) [65], "safety culture is an assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance". Typically, safety culture is set by management and trickles down, affecting performance at all levels, including the crew and other individuals.

8.4.6.3 Confidence in Information

This PIF refers to the team's belief in the information they have in terms of accuracy, validity, credibility, etc. The crew needs to have some level of confidence in the information they obtain from indicator reading, procedures etc. so that it can be used adequately.

8.4.6.4 Familiarity with or Recency of Situation

As a PIF, it refers to the perceived similarities between the current situation and the crew’s past experiences, training received and general industry knowledge [58]. This PIF can explain why the same task is assessed differently in terms of its complexity by different crew members. It may also bias the crew's assessment of the actual situation in favor of what they recall from their past experiences, training, etc.

8.4.6.5 Competing / Conflicting Goals

This PIF refers to the situation where the crew has different goals and objectives that are conflicting or competing. This may affect their choices and decisions based on their level of comfort with some of the options, or perceived workload, urgency, and impact.

8.4.7 Stress Group

As a PIF, stress refers to the tension / pressure [7] induced on the crew by their perception of the situation [66] or by the awareness of the consequences and responsibility that comes along with the decisions they make. As a PIF group, it is comprised of two level 2 PIFs namely: Stress due to Situation Perception and Stress due to Decision.

8.4.7.1 Stress due to Situation Perception

This PIF refers to the tension / pressure induced on the team by their assessment of the urgency (speed) and severity (magnitude) of the situation (which may be an undesired outcome e.g. system failure). This PIF is comprised of two level 3 PIF namely: Perceived Situation Urgency and Perceived Situation Severity.

8.4.7.1.1 Perceived Situation Urgency

As a PIF, it refers to the tension / pressure induced on the team by the assessment of the speed at which an undesired outcome (e.g. system failure) is approaching [32], or by the perception that the available time is inadequate to complete the task at hand. According to Wickens [67], it can also be viewed as the rate at which the situation at hand is moving towards the moment when a negative consequence will materialize.

8.4.7.1.2 Perceived Situation Severity

This PIF refers to the tension / pressure on the crew caused by their assessment of the magnitude of an undesired outcome (e.g. system failure) and its potential consequences. The undesirable outcome could adversely affect the crew, plant and the public in general [32].

8.4.7.2 Stress due to Decision

This PIF refers to the tension / pressure on the crew caused by the awareness of the responsibility that comes along with that particular decision and their perception of the impact / consequences of the decision on themselves, the facility and the society in general. Often times when there is a potential that major negative consequences could be involved, people tend to delegate their authority to made decisions to others for fear of being held accountable [67].

8.4.8 Task Load Group

As a PIF, Task load refers to the load induced on the crew by the actual demands of the assigned task in terms of the complexity of the task, quantity, importance, accuracy requirements per unit of time. The perceived level of this load is dependent on the proficiency level of the crew and their level of familiarity with the tasks [34]. It is also acknowledged that there may be cases where having too few tasks can lead to errors due to the crew's complacency. Task load is a component of the perceived workload [44], and the term “workload” seen in literature generally has a broader meaning than task load [68]. As a PIF group, it is comprised of four level PIFs namely: Cognitive complexity, Execution Complexity, Extra Workload and Passive Information Load.

8.4.8.1 Cognitive Complexity

This PIF refers to the cognitive demands [69] induced on the crew by the situation and assigned tasks in terms of the inherently complex nature of the task and that imposed by external factors. It is comprised of two level 3 PIFs namely: Inherent Cognitive Complexity and Cognitive Complexity due to External factors.

8.4.8.1.1 Inherent Cognitive Complexity

This PIF refers to the cognitive demands induced on the crew by the inherent complex nature of the problem being solved. Some tasks could be complex in nature, hence the crew may have difficulty understanding what is required of them in order to complete it.

8.4.8.1.2 Cognitive Complexity due to External factors

This PIF refers to the cognitive demands induced on the crew by external situational factors and conditions. In this instance, external factors /conditions like not having the proper tools to process information or make diagnosis may induce some mental demand on the crew.

8.4.8.2 Execution Complexity

This PIF refers to the physical demands induced on the crew by the situation and assigned tasks in terms of the inherently complex nature of the task or that imposed by external factors. It is comprised of two level 3 PIFs namely: Inherent Execution Complexity and Execution Complexity due to External factors.

8.4.8.2.1 Inherent Execution Complexity

This PIF refers to the physical demands induced on the crew by the inherent complex nature of the problem being solved. Some tasks could be naturally complex because too many steps are required for its completion.

8.4.8.2.2 Execution Complexity due to External factors

This PIF refers to the physical demands induced on the crew by external situational factors and conditions. The crew may have to complete a task in a very noisy or extreme high / low temperature environment and these factors may induce some physical demand on them.

8.4.8.3 Extra Workload

This PIF refers to the load induced on the crew by the extra work that has to be performed in addition to the main tasks. Note that the main tasks are those which are properly designed and the crew has adequate training to complete. While these extra work are relevant to the task (e.g. making or answering phone calls to report the current status of the system), they can also be viewed as interfering activities [43] which can cause distractions while completing the assigned task.

8.4.8.4 Passive Information Load

This PIF refers to the load induced on the crew by the amount of information and cues (e.g. indicators, alarms) that is presented to them by the external world [7]. When this load is high, it may lead to stimulus overload [70].

8.4.9 Time Constraint Group

As a PIF, time constraint refers to the crew's perception of the adequacy of the time available to complete the task at hand. It involves both the real duration of the task (which is the amount of time required to complete the task) and the perceived time (which is the crew's estimate of the available time). Obviously, there is the real duration (i.e. actual time required) and then the crew’s perception of that time. This perception of time can affect the crew’s stress level if it is estimated to be inadequate [71]. This PIF group only consists of itself “time constraint”.

9 CFM – PIF Framework Development

After defining the crew failure modes (CFMs), performance influencing factors (PIFs) groups and hierarchy, the next step was to develop a model that can be used to map them to each other. In order to accomplish this, there is a need to understand the mechanisms of human performance that could lead to failure, as well as how various contextual factors could influence the mechanisms and lead to undesirable human performance.

9.1 Background

PIFs could also be defined as contextual factors (which include plant factors) that influence the likelihood that the psychological failure mechanisms activate the processes that lead to proximate causes of macrocognitive function failures. In an effort sponsored by the US NRC to develop a tool that could be used to inform HRA, specifically to identify the relevant causes and contributors to failure in human cognition, Whaley et al. [72], [73], [74] conducted a thorough literature review of a broad range of cognitive models to identify categories of cognitive mechanisms that can lead to human failures in the different phases of human information processing and the contextual factors that can contribute to failures of those cognitive mechanisms. Its main product is an elaborate cognitive framework which establishes the connections between PIFs and the cognitive mechanisms that lead to failure in human performance. In order to show these connections, the literature review identified the following:

- Psychological / Cognitive failure mechanisms: These are the cognitive or psychological processes which could lead to failure when they are associated with contextual factors that promote error. They are identified for each proximate cause. Examples include cue context, change detection, and goal conflict).
- Proximate causes: These are categories of clusters of psychological failure mechanisms that can lead to failure in cognitive functions like detection, understanding, decision making, etc. Therefore, proximate causes are the consequence of psychological failure mechanisms and serves as the obvious indication of the more basic cause of failure to perform a function. Examples of proximate causes include cues / information not perceived, incorrect data and incorrect frames.
- Macrocognitive functions: These are the categories of clusters of proximate causes and they include detection/noticing, sense making/understanding, decision making, action implementation and team coordination. These functions overlap and dynamically interact with each other in a continuous, non-linear loop involving cyclical and parallel processes even though they are listed separately. The term "macrocognition" was originally created by [75] to explain cognitive tasks that occur in real world settings and research work in this area tries to show how to integrate smaller microcognitive models in order to explain how the human brain functions in complex settings.

This cognitive framework has four elements (macrocognitive functions, proximate causes, cognitive failure mechanisms, PIFs) and the mapping established between them has enabled the identification of how failures in human performance occur. For a given proximate cause of failure of a macrocognitive function, one can identify the cognitive failure mechanisms for the associated error and the PIFs that may activate the mechanisms involved. This mapping can be represented in the form of a table or a tree structure (fault tree tipped sideways) [72], [74]. It is important to note that the connections or links identified was based on information available, with the understanding that some links may be modified later on as more information becomes revealed in cognitive literature.

9.2 CFM – PIF Framework

Since the US NRC had already sponsored the development of this elaborate cognitive framework to support HRA (aimed at bridging the gap between HRA, psychology and cognitive sciences), we decided to adopt it and use it as a starting point in the development of this framework (instead of reinventing the wheel). The framework has 5 main elements which includes CFMs, Macrocognitive functions, Proximate Causes, Cognitive failure mechanisms and PIFs. The CFMs and PIFs have been discussed in previous chapters, so we will discuss the other elements of this framework in following sections.

9.2.1 Macrocognitive Functions

According to Klein et al., [76], macrocognition focuses on the nature of human performance. This is a “field” where decisions are often very complex, have to be made quickly, by domain experts, in risky situations. Microcognition, is typically focused on tightly controlled laboratory research, with the goal of explaining the building blocks that underlie more complex cognition. Many microcognitive models have been developed, and are focused on different aspects of the brain functions and human cognition. Macrocognition integrates the narrowly focused microcognition laboratory research findings into a larger picture, by explaining how the brain works in applied, complex settings. Microcognition has been used as a building block in this framework because it: is easily understood by HRA analyst; organizes the microcognitive models into a useable set of functions; useful when conducting predictive analyses of human performance in complex scenarios; can synthesize psychological research findings into a structure that yields a coherent understanding of the functions of human cognition and how it fails; integrates state-of-the art psychology and cognitive science into a foundation for HRA [72].

Many macrocognitive models have been developed including [11], [22], [76] - [78]. IDAC [11] and IDA [22] were developed for modeling operator performance in NPP domain and have been adopted as the human response model for this work. The five macrocognitive functions included in this framework are [72]:

- Detecting and Noticing: This is the process of perceiving important information in the work environment, with emphasis on the sensory and perceptual processes. These processes allow humans to perceive large amounts of information and focus selectively on the pieces that are pertinent to the present activities.
- Understanding and Sensemaking: This is the process of understanding the meaning of the information that has been detected. According to [76], sensemaking is a cyclical process that starts when a person or group of persons recognize that their current understanding of things is inadequate, typically when

one is surprised or an unexpected event occurs. It involves putting together pieces of information to form a complete understanding of a situation.

- Decision Making: This involves situation assessment, goal selection, diagnosis, evaluating options, selection, and response planning. With NPP, the process of decision making NPP usually involves experts and is largely driven by procedures.
- Action Taking: This involves the performance of an actual task in a NPP setting. It is necessary to specify the level of action implementation that is required for any function. According to [72], it is defined as implementing an action on the level of a single manual action (e.g. pushing a button) or a predetermined sequence of manual actions, and must involve the manipulation of the hardware and/or software that would consequently alter plant status.
- Team Coordination. In NPP, this involves interactions between the individual crew members that make up the team. It is important to note that team coordination is also considered a PIF in our PIF groups and hierarchy.

9.2.2 Proximate Causes

Proximate causes are identified as the immediate cause of the failure of a macrocognitive function. According to [72], they were developed as clusters of mechanisms based on their effect of failure. They provide answers to questions asked about the resulting effect of the failure of a mechanism. For example, the resulting effect of the failure to the understanding of the situation (Understanding / Sensemaking macrocognitive function) include; using incorrect data to understand the situation, incorrectly integrating the data, frames or frames with data, and using incorrect frame to understand the situation. They are also considered are categories of clusters of psychological failure mechanisms. They are the consequence of psychological failure mechanisms and serve as the obvious indication of the more basic cause of failure to perform a function.

9.2.3 Cognitive / Psychological Failure Mechanisms

These are the cognitive or psychological processes that can lead to human error. In this framework, these mechanisms are used to specify the means by which a failure mode can occur. These are the processes by which macrocognitive functions work and can lead to failure when associated with contextual factors that promote error. They are identified for each proximate cause in this framework. As an example, the mechanisms associated with the proximate cause "the use of incorrect data to understand the situation" includes: data not properly recognized, classified or distinguished, and attention to wrong / inappropriate information.

9.2.4 PIF Mapping

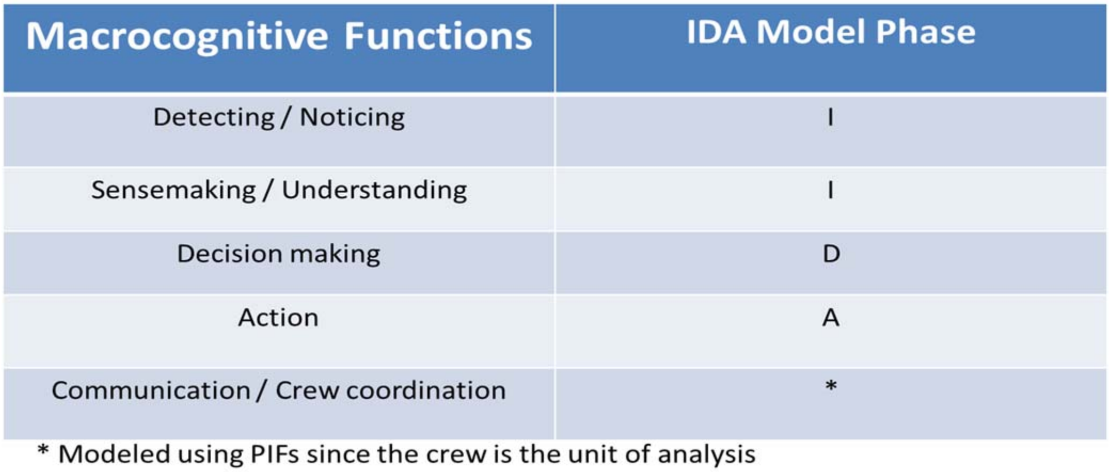
Since Groth's PIF set [32] was adopted for use by Whaley et al [72] as the PIF set of choice (i.e. the PIF set that is linked to the cognitive failure mechanisms in the framework), this made it easier to map our proposed PIF set (which was developed based on Groth's PIF set) to the cognitive failure mechanisms. However, not every PIF in Groth's set was included in the cognitive framework by [72]. According to [72], some were not included due to inability to link them to proximate causes and mechanisms with support from psychological literature. Also, some PIFs were added to the CFM-PIF framework that were not part of Groth's PIF set, some of which Groth had mapped from other HRA methods to her PIF set as discussed in [32].

In our CFM - PIF model, we made modifications to the list of PIFs that were included in the cognitive framework in [72]. We removed behavioral indicators like "proximity" and "anxiety" which were included as PIFs from our model since it is outside the scope of this research work. PIFs which Groth had already mapped to her set from other HRA methods were also removed and replaced with the equivalent ones that were defined in her's. Thereafter, we mapped the PIFs in our proposed grouping and hierarchy onto the modified PIFs.

9.2.5 CFM Mapping

IDA model (the cognitive model adopted for this research work) was one of the cognitive models reviewed by [72] to guide the adaption of macrocognition to the NPP operations. Hence, the macrocognitive functions can be mapped to different phases of the IDA model (Table 9-1).

Table 9-1: Mapping of Macrocognitive functions to IDA phases



Macrocognitive Functions	IDA Model Phase
Detecting / Noticing	I
Sensemaking / Understanding	I
Decision making	D
Action	A
Communication / Crew coordination	*

* Modeled using PIFs since the crew is the unit of analysis

We added an extra layer to the cognitive framework by linking the CFMs to the macrocognitive functions, thereby making the CFMs clusters of the macrocognitive functions. The mapping of the CFMs to the macrocognitive functions, proximate causes, cognitive failure mechanisms and the PIFs was done by selecting a particular CFM and examining how each of the macrocognitive functions influenced it based on cognitive psychology literature findings and our judgment. This was an iterative process which led to the creation of our initial CFM – PIF model by mapping of each CFM to PIFs influencing it through the relevant macrocognitive functions, proximate causes and cognitive failure mechanisms. Figure 9-1 shows an example of the tree structure for mapping the CFM (Incorrect Timing of Action) to the PIFs influencing it. See Appendix B for the complete tables showing our proposed mapping of each CFM to the PIFs influencing it.

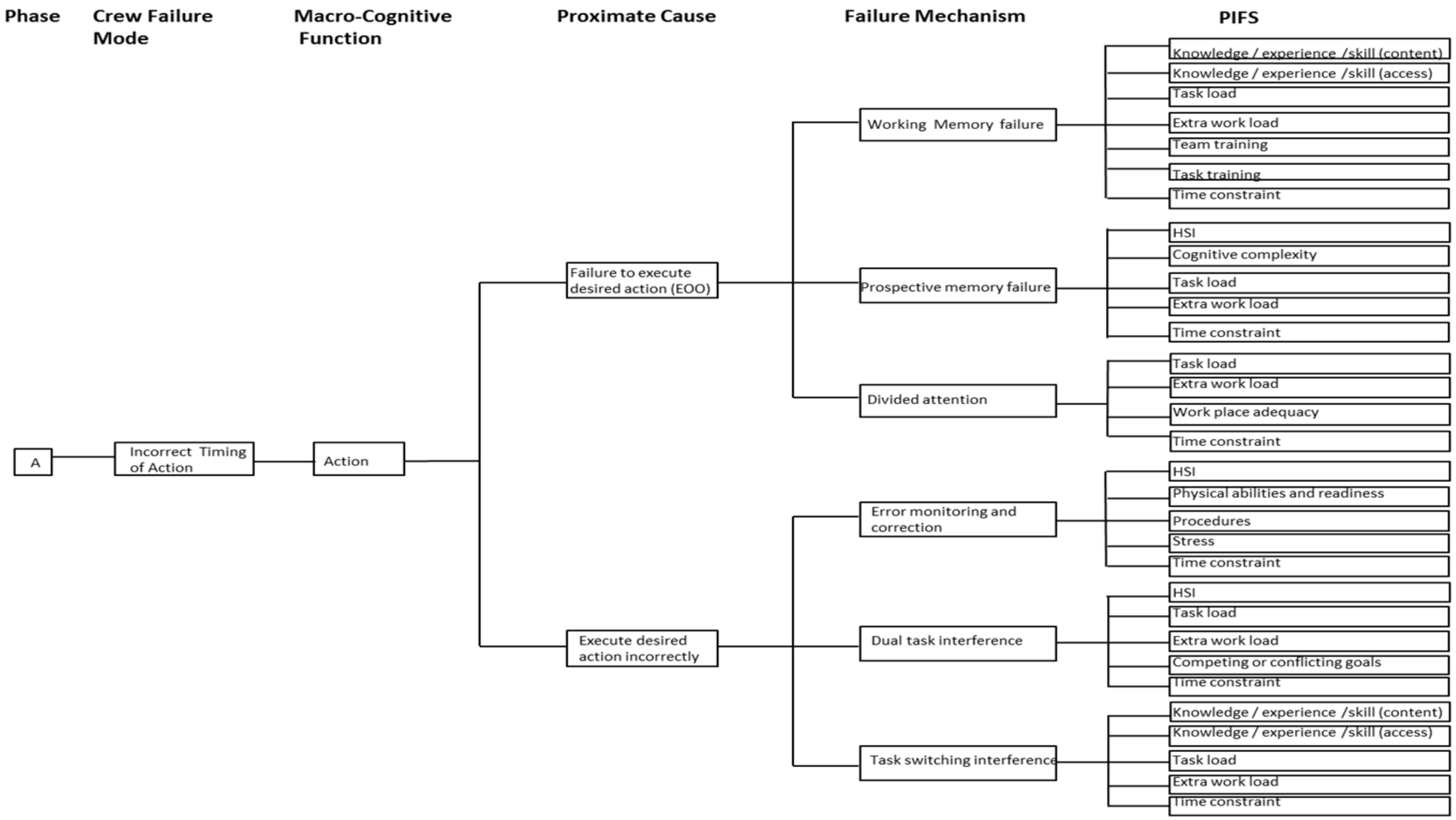


Figure 9-1: Tree structure showing the mapping of a CFM to PIFs

Note that the CFMs were defined to indicate crew failure in the different IDA phases. Each of these phases can be further decomposed into the form of a nested I-D-A structure. At the first level (which is that of the CFMs), I-D-A would represent failure in information received phase (I), decision made phase (D) and action performed phase (A). The (I) phase can in turn involve its own I-D-A sub structure. For example, failure in the recognition of the incoming information (I in I), decision on how the information should be processed (D in I) and acting in accordance with the decision (A in I). Similarly, the D and A phases can also have their I-D-A sub structures as well. Therefore, the macrocognitive functions identified by [72] may be represented by the IDA model (i.e. they form the second level I-D-A structure given that the CFM is the first level) See Table 9-2.

Table 9-2: Example demonstrating the nested IDA structure

CFM	Phase of crew/plant interaction (1st IDA phase)	Macrocognitive Function	2nd IDA phase
Key Alarm not Responded to	I	Detecting/Noticing	I
		Decision making	D
		Action	A

Using the cognitive framework produced by [72] as the basis for relating the CFMs to PIFs (i.e. developing our initial CFM –PIF model) was done to improve the qualitative analysis performed to support HRA quantification by focusing on the psychological and cognitive aspect of human performance. This aspect of human performance is important in crew's understanding and response to accident scenarios. It also improves the quantitative analysis by improving the understanding of the influence of the contextual factors (PIFs) and all the factors that needs to be modeled in order to estimate HEP. In addition, the mapping of the CFMs through the macrocognitive functions, proximate causes and failure mechanisms to the PIFs provides a means for developing a structured, causal model for the quantification approach proposed in this research work. This structured, causal model should aid in improving the consistency, traceability and reproducibility in results produced by different HRA analyst for the same scenario.

10 BBN Model Development

10.1 BBN Overview

A Bayesian belief network (BBN) is a type of probabilistic network used to represent the relationship between variables. Probabilistic networks are generally graphical models that are used to indicate the causal relationships and interactions between a set of variables. The nodes in the graph represent variables and the arcs (sometimes referred to as edges) indicate the direct dependencies (relationships) between the nodes. Therefore, a BBN consist of a set of nodes which represent variables and set of directed arcs which represent the direct causal relationships between the nodes. The variables and the directed arcs together form an acyclic directed graph [80].

BBNs have two aspects namely: the qualitative and the quantitative aspect. The qualitative aspect is represented by the structure of the network (i.e. the arrangement of the nodes and arcs to show the causal relationship between them [81]). The quantitative aspect involves the quantification of the strength of the causal relationship between the nodes probabilistically. This Chapter will focus on the qualitative aspect while chapter 12 will focus on the quantitative aspect of the BBN.

BBNs are becoming a popular part of the risk and reliability analysis discipline because of their ability to incorporate both qualitative and quantitative information from different sources for analysis. They provide the flexibility of updating the model (present state of knowledge) to incorporate new evidence as they become available. BBNs are a specific type of causal models and they are used to capture the stochastic and uncertain characteristics of a system. They provide a causal structure used for modeling interdependences among elements of the system. This causal structure can be used for causal reasoning (i.e. using the knowledge of the cause represented by a node in the network to determine the probability of the effect also represented by another node in the network), evidential reasoning (i.e. reasoning backward from the effect to the cause) and intercausal reasoning (i.e. the combination of causal and evidential reasoning used to provide insights into the process of determining mitigation factors) [82].

10.2 BBN Structure

The structure of a BBN represents the qualitative relationship between the variables in the network. Each variable is represented as a single node which is distinctively defined even if it is causally influenced by other nodes in the network. The relationships between these nodes are indicated using directed arcs. Two nodes are connected if one influences, affects or causes the other and the directed arc indicates the direction of the effect.

Two main steps are involved in the development of a causal model in the case of a BBN. The first step involves the identification of the variables to be included as nodes in the model. The second step involves the identification of the relationships between the nodes using arcs with arrow heads indicating the direction of influence.

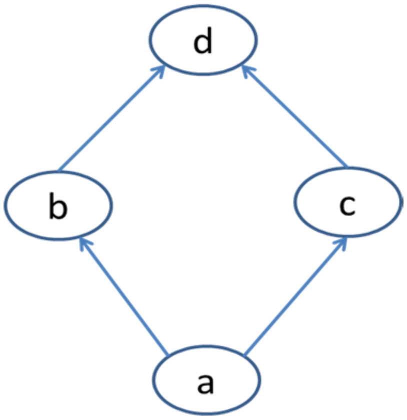


Figure 10-1: Sample BBN diagram

Figure 10-1 indicates a BBN with 4 nodes namely: *a*, *b*, *c*, and d. Node *a* is a root node (i.e. it has no arcs pointing into it). Node *d* is an end node (i.e. it has no arc pointing out of it). Node *a* serves as a parent node to nodes *b* and *c* (i.e. these nodes are its children). Nodes *b* and *c* serve as parent nodes to node *d*. This implies that node *a* has no parent but has two children (nodes *b* and *c*). Node *b* has a parent (node *a*) and one child (node *d*). Node *c* also has a parent (node *a*) and one child (node *d*). Node *d* has two parents (nodes *b* and *c*) and no child.

10.3 BBN Representation of the PIFs

We constructed a BBN to represent our PIF grouping and hierarchy (Figure 10-2). The variables included as nodes are the PIFs and the directed arcs are used to represent the relationship between the nodes as indicated by the different levels of the PIF (Table 8-1). In the model (Figure 10-2), the blue color nodes represent the level 1 (main PIF groups), brown color nodes represent the level 2 PIFs while the orange color nodes represent the level 3 PIFs.

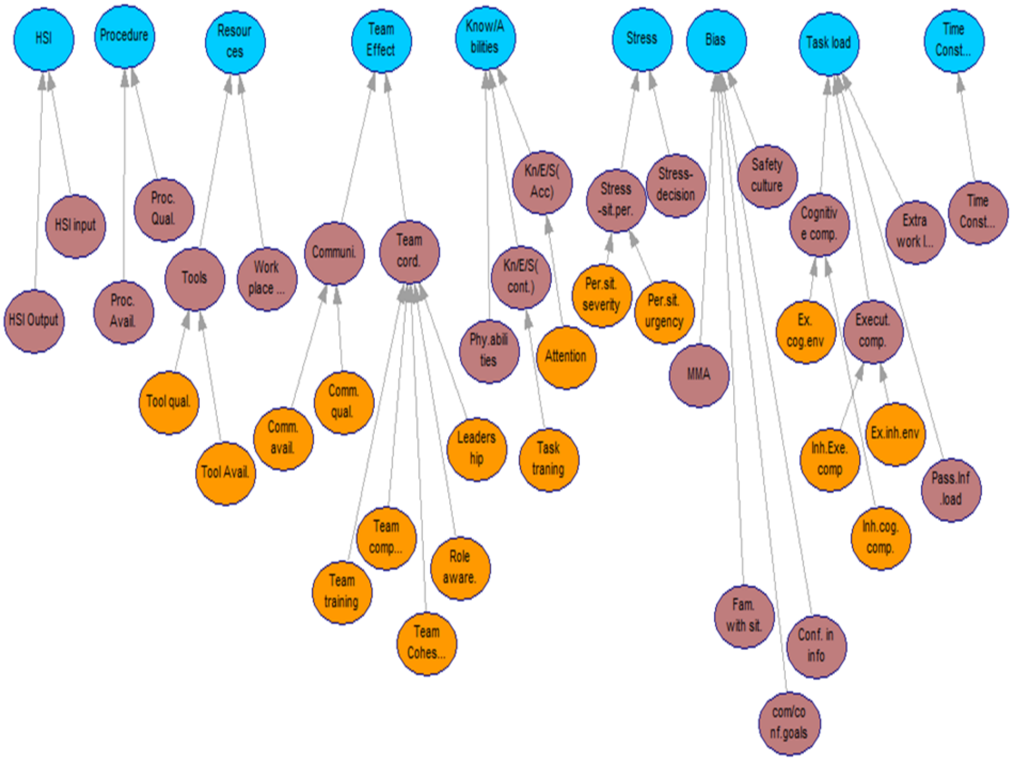


Figure 10-2: BBN representation of the PIFs

10.4 Master CFM – PIF BBN Model Construction

In this research work, the two main groups of variables to be included as nodes are PIFs and CFMs since the primary purpose of our BBN is to model the effect of the PIFs on the CFMs. This BBN model (Figure 10-3) is constructed using the variables (CFMs and PIFs) and the relationships indicated in the CFM-PIF framework (Appendix B). It shows the path of influence of the PIFs on each other and also on the various CFMs. Note that we have included the level 3 PIFs in this BBN model and their relationship with the level 2 PIFs (directed arcs from the level 3 PIFs to the level 2 PIFs) is based on our PIF grouping and hierarchy indicated in Table 8-1. Referring to the Master BBN model (Figure 10-3), the CFMs nodes are shown in green, level 1 (main PIF groups) in blue, level 2 PIFs in brown color and level 3 PIFs in orange color. Therefore, this is our proposed Master BBN model which shows the relationships between the CFMs and all the levels of PIFs defined in our methodology.

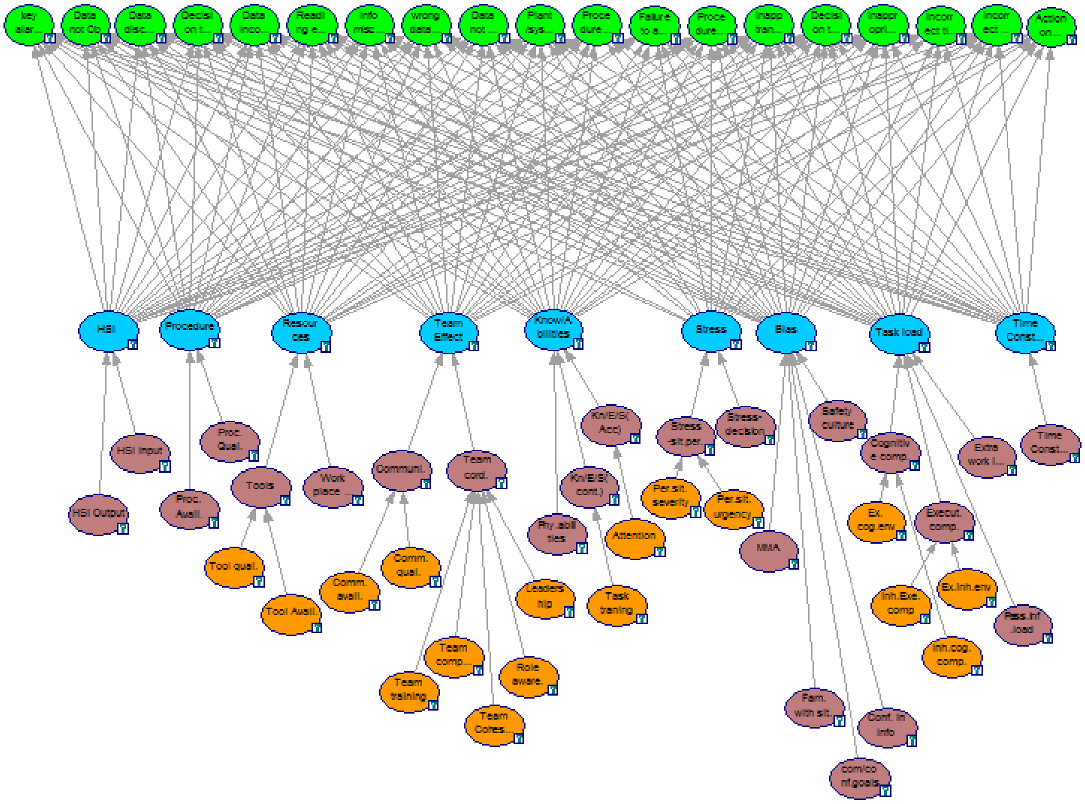


Figure 10-3: Master CFM-PIF BBN Model

The CFM nodes in the Master BBN model and the CFM basic events in the FTs associated with branch points of the CRT are obviously the connection between the PIF hierarchy and the rest of the qualitative analysis modules. By this illustration, the HFE scenarios identified through CRT and CFM fault trees are now extended to include the last layer of “causal factors” (i.e. the set of PIFs).

10.5 CFM – Main PIF Group BBN Model Construction

Using the top two layers (CFM and Main PIFs) of the Master BBN model, Figure 10-3, we constructed the CFM - main PIF group BBN model (Figure 10-4). The variables included as nodes are the level 1 (main PIFs groups) in blue color, and CFMs in green color. According to our CFM-PIF framework, each CFM is influenced by all the main PIFs. Therefore, the directed arcs which go from the main PIFs to the CFMs represent the relationship between these variables.

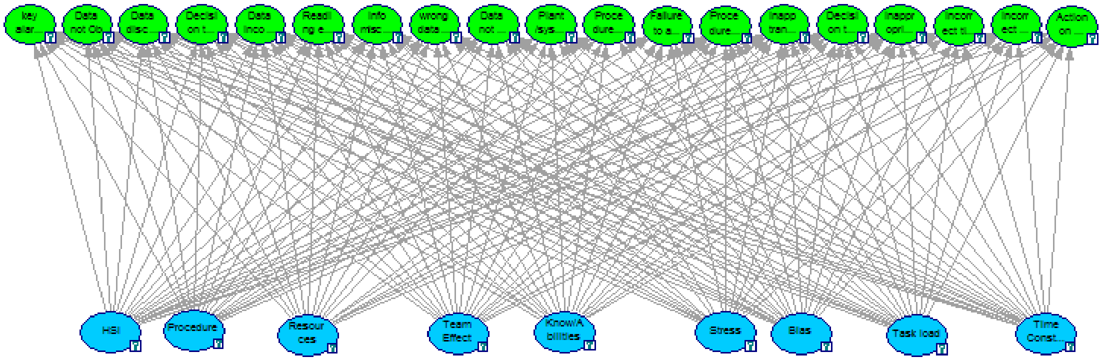


Figure 10-4: CFM-Main PIF BBN Model

There are two approaches to building this BBN model. One approach will involve developing a BBN model of the effect of PIFs on each CFM (this implies building 19 BBN models in this case). The second approach involves developing a single BBN model which includes all the CFMs. The second approach was adopted in this research work because it considers the effect of interdependency among the PIFs and CFMs which should not be ignored in HRA. Due to this notion of interdependency and other advantages of BBN discussed earlier in this chapter, the use of BBN became the proposed option among a number of alternatives such as use of tables (as it is done in many HRAs) or binary decisions trees (BDT) as used in the CBDT method for modeling the effects of the PIFs on CFMs. In other words, the CRT/FT formalism does not in itself require the use of BBNs for PIF modeling, but the proposed option addresses a number of outstanding HRA issues such as modeling various dependencies in an elegant and effective way.

11 Overview of the Quantitative Analysis Process

It is generally agreed that qualitative analysis is very important in the practice of HRA as it provides a basis for the evaluation of the crew performance in its interaction with the system and also provides possible suggestions for improvement. There is also a need to express the results of the analysis in quantitative terms since it is conducted in the context of a PRA. Since the results obtained from PRAs are frequently used to drive risk informed decision making processes, it is important to obtain consistent HRA results for inclusion in PRAs. Hence, we are providing a clear and systematic approach to quantification.

11.1 The Integrated Model

As discussed in previous chapters, the qualitative analysis framework has three layers. The crew response tree (CRT) represented by an event tree, forms the top layer. The human response model (IDA model) which is modeled using fault trees (FT) forms the second layer. Each branch point in the CRT is quantitatively linked to its own instance of the CFM FTs, noting that the FTs need to be pruned in order to satisfy the conditions of the relevant CRT branch point (since the FTs were developed as a template to satisfy all conditions). The basic events in the FTs are the CFMs which denote the ways in which crew failures occur at the CRT branch points. This approach of linking the FTs to the CRT will help identify the crew-plant interaction scenario cut-sets. The CFMs are linked to the PIFs, which forms the third layer of the framework through the CFM – PIF framework. The CFM- PIF linkage is modeled using a BBN. These three layers (CRT, FT & BBN) are combined together to form the integrated model illustrated in Figure 11-1.

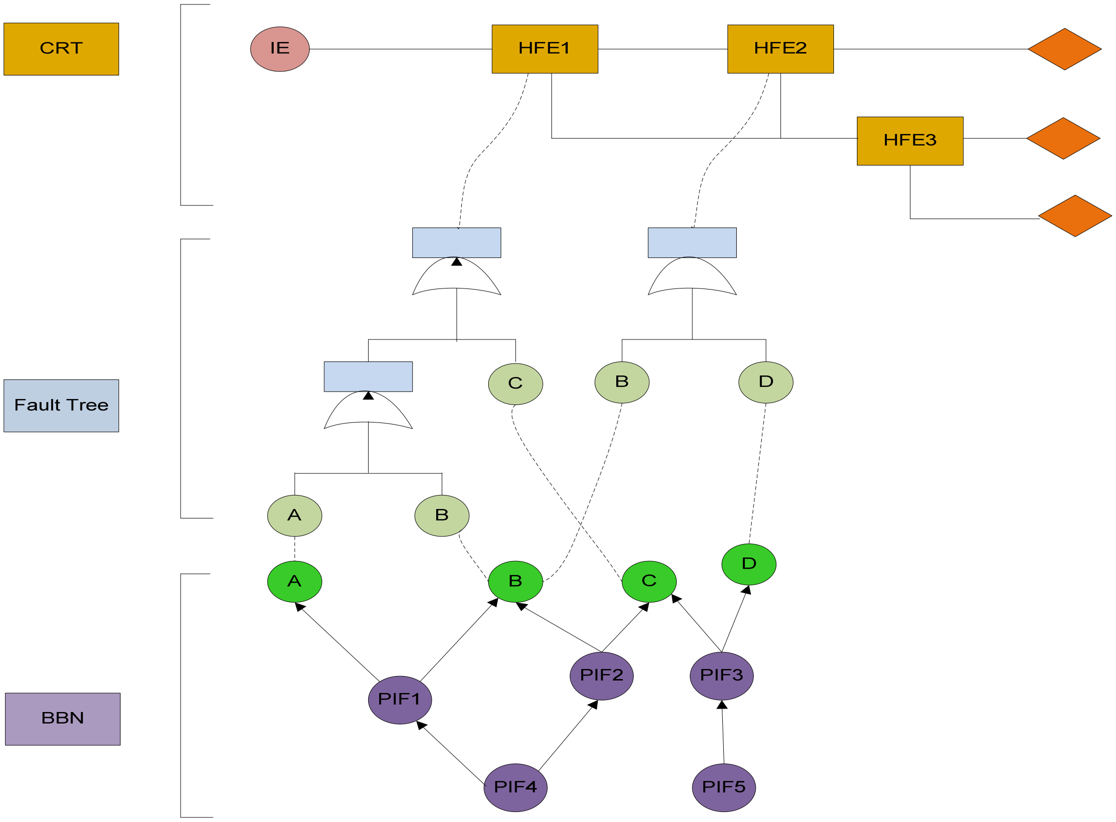


Figure 11-1: Sample diagram of the integrated model

11.1.1 The role of IRIS Software in Quantification

Integrated Risk Information System (IRIS) software tool can be used to support the quantification process. This tool was built by the Center for Risk and Reliability at the University of Maryland, College Park to support PRA and safety monitoring of complex socio-technical systems. It uses a three-layer hybrid causal logic (HCL) modeling approach [83] which allows the application of different PRA modeling techniques to various aspects of the system. The HCL approach combines the techniques for modeling deterministic causal paths with the flexibility of modeling non-deterministic cause-effect relationships among system elements [84]. Deterministic causal paths are modeled using event sequence diagrams (ESD) which are similar to ETs and FTs while the non-deterministic cause-effect relationships are modeled using BBNs.

The ESD (1st layer) is used to construct the CRT sequences, FT (2nd layer) to build the FTs which link the CFMs to CRT branches and the BBN (3rd layer) to build and quantify our BBN models. Therefore, the integrated model (CRT, FT & BBN) is solved using the hybrid causal logic approach provided by IRIS software.

11.2 Summary of the Analysis Procedure

The HRA quantitative analysis process broadly involves the estimation of human error probabilities (HEPs) for human failure event (HFE) of interest. From our qualitative analysis process, we obtain CFM cut-sets (which are the minimal combination of CFMs that could lead to the HFE of interest) and the list of PIFs that the HRA analyst has identified as being relevant to CRT scenarios used to model the HFE. These CFM cut-sets and PIFs are the inputs to our quantitative analysis process.

We are quantifying the CFMs in order to obtain the estimated HEP for the HFE of interest. The two options for quantifying the CFMs are:

- Direct assessment: The direct assessment approach entails directly obtaining the probability of CFMs. Thereafter, the values are used as base values but can be modified using PIF values in order to account for the effect of the relevant PIFs on the CFM in question. The modification could be done using some form of mathematical formulation and /or worksheets, just like what is obtainable in most first and second generation HRA methods.

- Through a BBN model: This involves constructing a BBN by using the CFMs and PIFs as nodes and the arcs to show the relationship between them. We decided to use this option for quantification because the BBN provides numerous benefits which includes: the ability to incorporate both qualitative and quantitative information from different sources for analysis; a causal structure for modeling interdependencies among elements of a system; the flexibility of updating the model (present state of knowledge) to incorporate new evidence as they become available; the capability of reasoning under uncertainty; and its ability to interface with existing event /fault tree (ET/FT) PRA models.

Hence, the quantitative model is a BBN model which was developed in the previous chapter. The quantitative analysis process can be generically defined using the following steps:

- **Identification of the relevant CFMs in the CFM – PIF BBN model:** The BBN model contains 19 CFMs and for a particular HFE, not all of them are relevant. For a particular HFE, the CFMs which are relevant are identified as part of the qualitative analysis process and they form the CFM cut-sets. These CFMs are considered “relevant CFMs” because they are ones that will be quantified in order to obtain the HEP. Hence, they need to be identified in the model. The other CFMs are considered “non-relevant” to the HFE and this information needs to be incorporated into the model.

- **Identification of the relevant PIFs in the CFM - BBN model:** Just as in the case of CFMs, not all PIFs are relevant to the particular HFE. Therefore, the "relevant PIFs" need to be identified in the model.
- **Assessment of the relevant PIF levels:** The levels of each of the relevant PIFs need to be assessed by the HRA analyst (using the tables provided for each PIF) and then inputted into the model for each PIF.
- **Determination of the temporal ordering of the relevant CFMs:** The order in which the CFMs occur is an important factor in the quantification process. The HRA analyst has to determine if the CFMs will be quantified with consideration for dependency or not in order to choose the right procedure for quantification.
- **Estimation of the conditional probabilities of the relevant CFMs:** The next step in the process is to estimate the conditional probabilities of the CFMs.
- **Estimation of the HEP for the HFE of interest:** The final step in the analysis process involves the incorporation of the conditional probabilities of the relevant CFMs into the logic equation of the CFM cut-sets in order to obtain the estimated HEP for the HFE of interest.

In the subsequent chapters of this dissertation, we'll discuss in detail the steps of this analysis process including data sources, model parameter estimation and provide some examples of the model run.

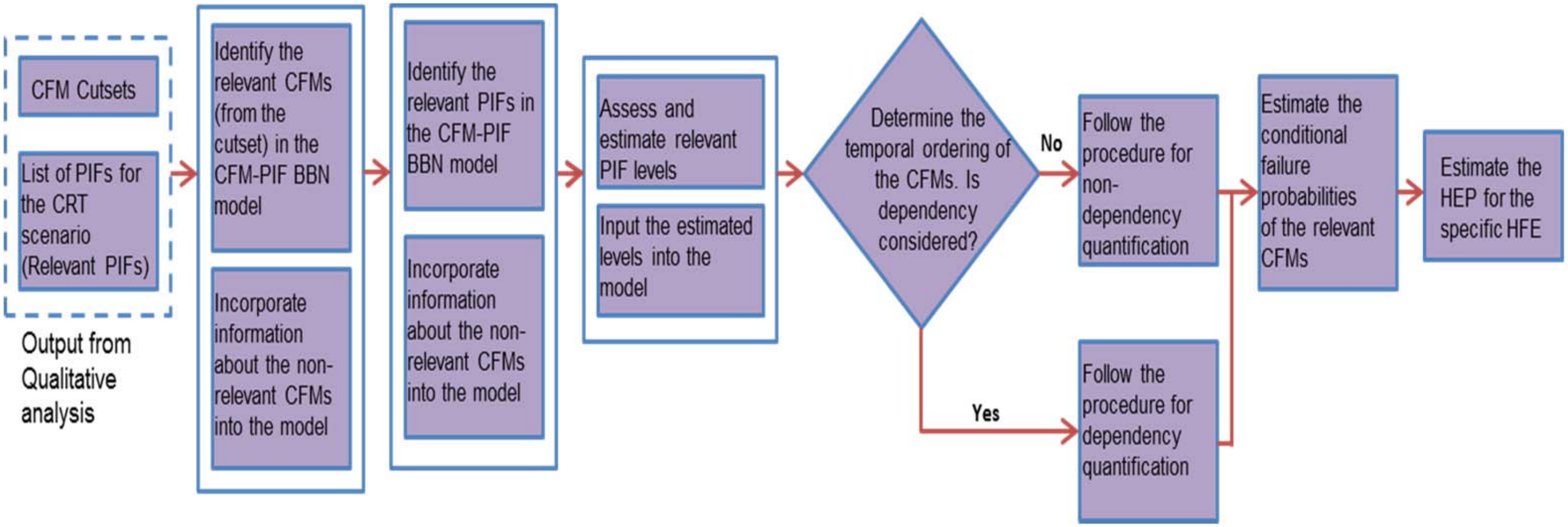


Figure 11-2: Overview of the Quantitative Analysis process

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12 BBN Model Quantification

This involves the quantification of the strength of the causal relationship between the nodes in the network probabilistically. After all the relationships between the nodes in a BBN are determined (i.e. the model is fully developed), each node gets assigned a marginal or conditional probability table (CPT), depending on its location in regards to other nodes in the network. Each node in a discrete BBN has a finite number of possible states and it is assigned a probability distribution based on the possible states of its parent nodes. Note that the sum of the marginal probabilities of all the states within the same node must be equal to 1.

Referring to Figure 10-1, the root node a would be quantified using the marginal probabilities of its states. For example, let's assume that node a has two possible states. Therefore, the marginal probabilities would be $Pr(a)$ = p and $\Pr(\overline{a})$ = 1 - p. Nodes with one or more parents (*b, c, d*) would be quantified using CPTs. The size of the CPT for each node depends on the number of states of the node, number of parents for the node, and the number of states of the parent nodes. For a binary node with n parents (each parent node is also binary), number of required conditional probabilities = 2^{n+1}. For example, the CPT for *b* (with a single parent *a*) is given below. Note that each column in the CPT must be equal to 1.

Table 12-1: CPT for node *b* given parent *a* in Figure 10-1

	Parent (*a*)	$\Pr(a)$	$\Pr(\overline{a})$
Child (*b*)	$\Pr(b)$	$\Pr(b\|a)$	$\Pr(b\|\overline{a})$
	$\Pr(\overline{b})$	$\Pr(\overline{b}\|a)$	$pr(\overline{b}\|\overline{a})$

12.1 BBN Quantification Overview

Mathematically, A BBN is a quantitative causal model which is used to represent the joint probability distribution of a universe of events **U** = (U_1,...,U_k), in terms of a set of system variables (nodes) **V** = (V_1,…,V_n), a graph and the conditional probability distributions [85]. The chain rule, equation (12-1) is utilized by the BBN model to calculate the joint probability of the variables from the conditional probability distributions. It indicates that the probability distribution over a set of variables (known as the joint probability distribution) P(**V**) can be calculated as a product of conditional probabilities distributions:

$$P(V) = P(V_1, V_2, \dots, V_n) = P(V_1)\, P(V_2|V_1) \dots P(V_{n-1}|V_1, V_2, \dots, V_{n-2})\, P(V_n|V_1, V_2, \dots, V_{n-1}) \tag{12-1}$$

Due to the conditional independence statements in the BBN (i.e. each child node is conditionally independent of all its non-descendants given its parent nodes, pa), the BBN specifies a unique joint probability distribution, equation (12-2), (which simplifies the scope of the conditional probability distributions) calculated as the product of all the conditional probability tables (CPTs) specified in the BBN [80], [85]:

$$P(V) = P(V_1, V_2, \dots, V_n) = \prod_{i=1}^{n} P(V_i\,|\,pa(V_i)) = P(V_1|pa(V_1))\, P(V_2|pa(V_2)) \dots\, P(V_n|pa(V_1)) \tag{12-2}$$

Note that pa(V_i) are the parents of V_i in the BBN model.

12.1.1 Bayesian Updating

One of the benefits that the BBN offers as a modeling tool is the flexibility of updating the model (i.e. the present state of knowledge) to incorporate new evidence as it becomes available. This ability to update the model is embedded in the use of Bayes’ Theorem [80], [82], [87], equation (12-3).

$$P(M|N) = \frac{P(N|M)P(M)}{P(N)} \tag{12-3}$$

Bayes’ Theorem which is the heart of Bayesian inference provides the ability to estimate the conditional probability of N|M from that of M|N and vice versa. This implies that the BBN can be used to conduct multiple types of inferences or reasoning which includes causal reasoning from M to N, evidential reasoning from N to M and intercausal reasoning (combination of causal and evidential reasoning) [82], [88], [89]. This ability to reason about specific events is very useful in HRA. The HRA analyst would implement causal reasoning by using the knowledge of PIFs to estimate the probability of the HEP for the specific HFE. Also, evidential reasoning which is actually the ability to reason backwards from the effects (human error) to the causes (PIFs) gives the HRA analyst the ability to identify the PIFs that greatly degrade human performance and hence most directly contributed to the occurrence of the HFE. This is also useful when conducting analysis to provide insights on how to prevent HFEs [85].

12.2 Overview of our BBN Model Quantification

Building a master network like the master BBN model (Figure 10-3) often requires a careful trade-off between the desire to build a large and comprehensive model that includes every little detail to obtain the highest level of accuracy possible, and the feasibility, the cost of construction in terms of time and resources needed, and the complexity of probabilistic inference [86]. Given its complexity in terms of the number of nodes in the network (over 60), the number of arcs (over 200), the size of the CPTs, it will be extremely difficult to properly quantify this model. Therefore, our quantification methodology will be focused on the CFM – Main PIF BBN model, Figure 10-4. For the purposes of the quantification and hence forth in this dissertation, we will be referring to this model as “The BBN model”. Also, we are repeating the diagram of the model here, but the names of the CFMs nodes changed to represent their respective IDs in the model. This model will be used for further reference in this work. It has 19 CFMs and 9 PIFs (Figure 12-1). Each node in the model has two states. Each CFM has a success and failure state. The success state implies that the specific CFM has not occurred (i.e. the crew has not failed in that instance) while the failure state implies that the specific CFM has occurred (i.e. the crew has failed in that instance).

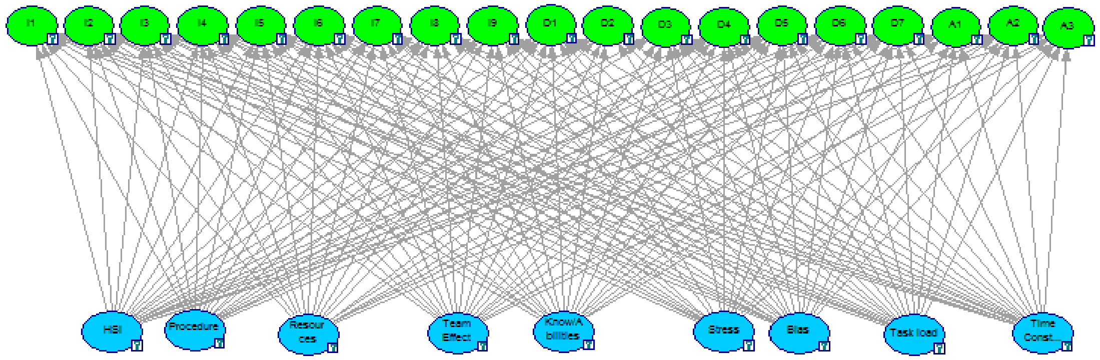


Figure 12-1: The BBN Model

The joint probability distribution encoded in the BBN model for each CFM is given by equation (12-4):

$$P(CFM \cap PIF_1, PIF_2, \ldots, PIF_9) = P(CFM|PIF_1, PIF_2, \ldots, PIF_9)\, P(PIF_1)\, P(PIF_2) \ldots P(PIF_9) \tag{12-4}$$

This joint probability distribution expression is substantially simpler than one that would have resulted from the direct application of the chain rule, equation (12-1).

In HRA, quantification involves the estimation of the human error probability (HEP) for a particular human failure event (HFE). An HFE is the result of one or several sequences of events (overall context) for any given plant PRA scenario (S) in accordance with the CRT and corresponding linked causal models. To be consistent with a scenario-based approach, the HEP can be estimated using the following expression which provides a conceptual link between the qualitative and quantitative aspects of HRA [6]:

$$P(HFE|S) = \sum_{i=1}^{I} P(HFE|CFM_i) \left\{ \sum_{j}^{J} P(CFM_i|F_{j1}, F_{j2}, \ldots, F_{jn}; S) \times P(F_{j1}, F_{j2}, \ldots, F_{jn}|S) \right\} \tag{12-5}$$

- The summation in the brackets indicates the probability of i-th CFM considering all possible CRT scenarios (j = 1, 2, …, J) that leads to the particular HFE of interest. Each scenario is characterized by a set of n factors (or different instances of a fixed super set of factors). The set $\{F_{j1}, F_{j2}, \ldots, F_{jn}; S\}$ includes the usual PIFs and everything else in the scenario context (e.g. elapse time in a scenario, specific crew action etc.) that affect the probability of HFE.
- The term $P(CFM_i | F_{j1}, F_{j2}, \ldots, F_{jn}; S)$ is the probability of i-th CFM given the context for a particular CRT scenario S, and $P(F_{j1}, F_{j2}, \ldots, F_{jn} | S)$ is the probability of the context given the particular PRA scenario S.

- The CFMs can be defined in such a way that $P(HFE \mid CFM_i) = 1$ for all "i". In this case the aim of the HRA quantification model would be to assess the values of $P(CFM_i \mid F_{j1}, F_{j2}, \ldots, F_{jn} ; S)$ and $P(F_{j1}, F_{j2}, \ldots, F_{jn} \mid S)$ for each sub-context j. Hence, the HEP can then be estimated using the following expression:

$$P(CFM|S) = \sum_{j=1}^{J} P(CFM|F_{j1}, F_{j2}, \ldots, F_{jn}) \times P(F_{j1}, F_{j2}, \ldots, F_{jn}|S) \tag{12-6}$$

Therefore, according to equation (12-6), we need the values of $P(CFM \mid F_{j1}, F_{j2}, \ldots, F_{jn})$ and $P(F_{j1}, F_{j2}, \ldots, F_{jn} \mid S)$ in order to estimate the HEP for any HFE of interest.

In relation to the BBN model (Figure 12-1),

- $P(CFM \mid S)$ i.e. the estimated HEP, represents the output of our quantified BBN model. This output is the joint probability distribution of the CFMs and PIFs i.e. $P(CFM \cap PIF_1, PIF_2, \ldots, PIF_9)$ for each of the 19 CFMs.
- The term $P(F_{j1}, F_{j2}, \ldots, F_{jn} \mid S)$ represents the conditional probability of the different states (two in this model) of each of the nine main PIFs i.e. $P(PIF_1)$, $P(PIF_2)$, …, $P(PIF_9)$. This is the data required to complete the marginal probability table for each main PIF node.
- The term $P(CFM \mid F_{j1}, F_{j2}, \ldots, F_{jn})$ represents the probability of the different combinations of $P(CFM \mid PIF_1, PIF_2, \ldots, PIF_9)$ for each of the 19 CFMs. This is the data required for the conditional probability table for each CFM node.

12.3 Assessment of PIFs Levels

Part of the output of the qualitative analysis is the list of the PIFs that the HRA analyst has determined to be relevant to the CRT scenario of interest. These PIFs are determined to influence the crew's performance throughout the scenario. Each PIF in the BBN model has two states. One state is the nominal state in terms of its influence on the CFMs (crew performance). In this context, "nominal" implies that the PIFs do not have a significant influence on the crew's performance (i.e. they do not improve or degrade their performance ideally). The second state of the PIFs is the state that influences the crew's performance by degrading or reducing it (i.e. it enhances crew failures). Table 12-2 shows the level descriptor for the main PIFs and their expected effect on crew performance.

Table 12-2: PIF levels and effect on crew performance

PIF	Level	Effect on crew performance
Human System Interface (HSI)	Adequate	Nominal
	Inadequate	Degrade
procedures	Adequate	Nominal
	Inadequate	Degrade
Resources	Adequate	Nominal
	Inadequate	Degrade
Team Effectiveness	Effective	Nominal
	Ineffective	Degrade
Knowledge / Abilities	Adequate	Nominal
	Inadequate	Degrade
Bias	Low	Nominal
	High	Degrade
Stress	Low	Nominal
	High	Degrade
Task load	Low	Nominal
	High	Degrade
Time constraint	Nominal	Nominal
	High	Degrade

In order to aid the HRA analyst in the assessment of the level of each main PIF, we have provided a list of questions (Table 12-3 - Table 12-11) which are relevant to each of these PIFs. These questions aid the HRA analyst to represent a continuous variable (PIFs levels in the model) with point estimates. These questions are primarily made up of the information on the level 2 and 3 PIFs. Therefore, even though the level 2 and 3 PIF are not directly included as nodes in the version of the BBN model used for quantification, they are used in the assessment of the main PIFs (which are nodes in the quantified BBN). Hence, we are still capturing the information that these PIFs (level 2 and 3) provide in our quantification framework (indirectly).

12.3.1 PIF Assessment Questionnaires

The tables in this section contain questions that would aid the analyst in estimating the marginal probability levels of the PIF nodes in the BBN. Note that sophisticated social science survey instruments may be needed to support the HRA analyst's answer to some of these questions.

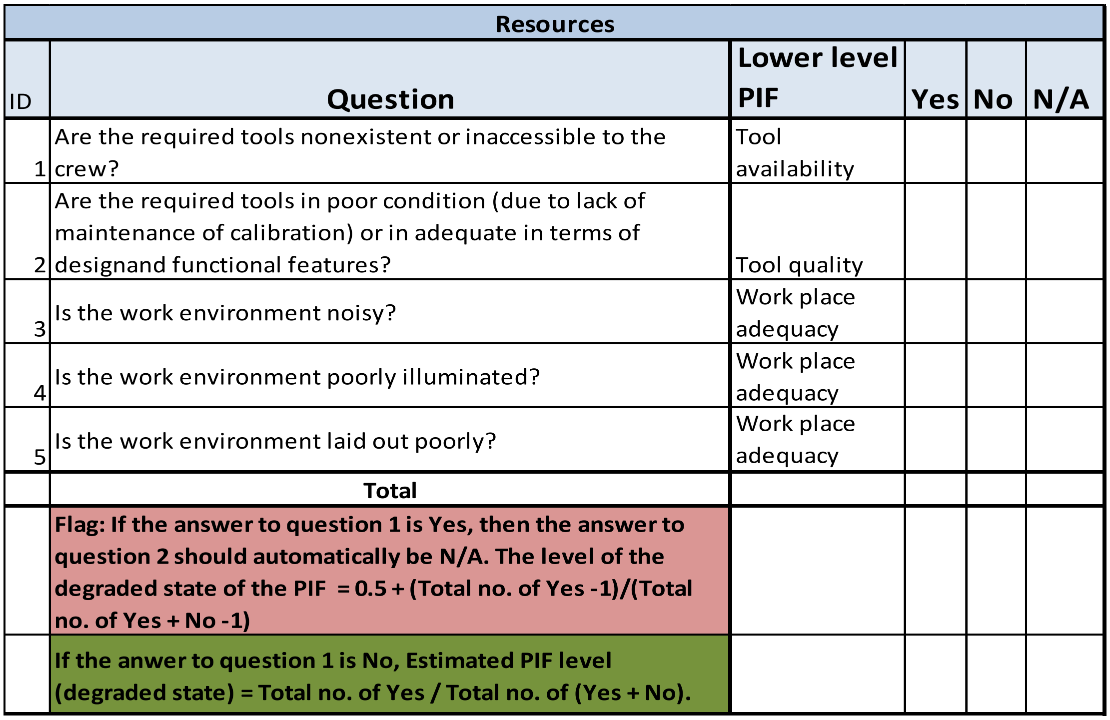
Table 12-3: HSI assessment questionnaire

HSI					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Is the alarm unavailable, not prominent, not distinctive and ambiguous? Is the alarm difficult to detect from background noise and other alarms/information and is its relevance evident?	HSI output			
2	Are the indications / sources of data unavailable, unclear and ambiguous (give misleading or conflicting information)?	HSI output			
3	Is the range (or band) with which the information is to be compared unclearly identified on the display?	HSI output			
4	Is the environment in the location of the indicator/source of information degraded (i.e., challenging due to noise, heat, humidity, etc.)?	HSI output			
5	Are the indicators/sources of data difficult to read?	HSI output			
6	Are slight changes difficult to detect?	HSI output			
7	Is it a spurious alarm e.g. sensor failure triggered the alarm?	HSI output			
8	Is the relevant information not properly distributed over time/space?	HSI output			
9	Is the system feedback inadequate, e.g,. the response time is it too long?	HSI output			
10	Are the controls non-distinctive?	HSI output			
11	Do the controls operate differently from standard controls or normal conventions?	HSI output			
12	Is the system designed such that it is difficult to input information like turning a dial, pushing a button or entering commands on a key board?	HSI input			
	Total				
	Flag 1: If the answer to question 1 or 2 is Yes, then the level of the degraded state of the PIF = 0.5 + (Total no. of Yes -1)/(Total no. of Yes + No -1).				
	Flag 2: If the answer to questions 1 and 2 is Yes, then the level of the degraded state of the PIF = 1. No need to continue going through the questions.				
	If the answer to questions 1 and 2 is no, then, estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Table 12-4: Procedures assessment questionnaire

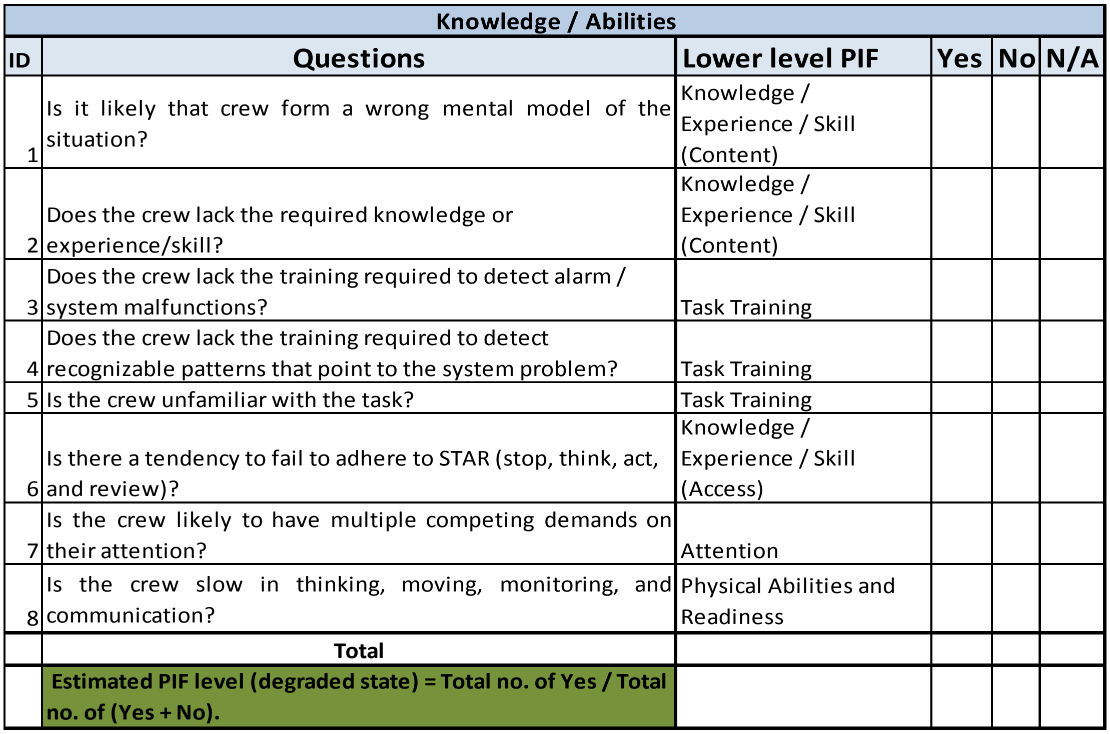
Procedures					
ID	Questions	Lower level PIF	Yes	No	N/A
1	Are the required procedures unavailable?	Procedure availability			
2	Does the primary procedure (i.e. the main procedure being used) lack all the necessary instructions?	Procedure quality			
3	Is there a Procedure-Scenario Mismatch i.e. the plant conditions do not match procedure assumptions?	Pocedure quality			
4	Does the procedure provide conflicting guidance ?	Procedure quality			
5	Are there confusable words included in the procedures such as "increase" and "decrease"?	Procedure quality			
6	Is the procedure ambiguous in its meaning? If the steps are not clear or lack details for the desired action in the context of the sequence of interest, then the procedure is ambiguous. A procedure may also be judged as being ambiguous if acceptance / success criteria and tolerances or specific control positions and indicator value are not properly specified.	Procedure quality			
7	Does the procedure contain double-negatives?	Procedure quality			
8	Are charts, graphs, or figures within the procedure difficult to read or understand?	Procedure quality			
9	Does the procedure prompt a situation in which the crew is required to perform calculations or make other manual adjustments without the aid of worksheets?	Procedure quality			
	Total				
	Flag 1: If the answer to question 1 is Yes, then set the level of the degraded state of the PIF to 1. there is no need to continue going through the questions.				
	Flag 2: If the answer to question 1 is No and the answer to question 2 is Yes, then the level of the degraded state of the PIF = 0.7 + (Total no. of Yes -1)/(Total no. of Yes + No -2). Note that if (Total no. of Yes - 1)/(Total no. of Yes + No -2) is greater than 0.3, it should be normalized to 0.3.				
	If the answer to questions 1and 2 is No, then, estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Table 12-5: Resources assessment questionnaire



Resources					
ID	Question	Lower level PIF	Yes	No	N/A
1	Are the required tools nonexistent or inaccessible to the crew?	Tool availability			
2	Are the required tools in poor condition (due to lack of maintenance of calibration) or in adequate in terms of designand functional features?	Tool quality			
3	Is the work environment noisy?	Work place adequacy			
4	Is the work environment poorly illuminated?	Work place adequacy			
5	Is the work environment laid out poorly?	Work place adequacy			
	Total				
	Flag: If the answer to question 1 is Yes, then the answer to question 2 should automatically be N/A. The level of the degraded state of the PIF = 0.5 + (Total no. of Yes -1)/(Total no. of Yes + No -1)				
	If the anwer to question 1 is No, Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Table 12-6: Knowledge / Abilities assessment questionnaire



Knowledge / Abilities					
ID	Questions	Lower level PIF	Yes	No	N/A
1	Is it likely that crew form a wrong mental model of the situation?	Knowledge / Experience / Skill (Content)			
2	Does the crew lack the required knowledge or experience/skill?	Knowledge / Experience / Skill (Content)			
3	Does the crew lack the training required to detect alarm / system malfunctions?	Task Training			
4	Does the crew lack the training required to detect recognizable patterns that point to the system problem?	Task Training			
5	Is the crew unfamiliar with the task?	Task Training			
6	Is there a tendency to fail to adhere to STAR (stop, think, act, and review)?	Knowledge / Experience / Skill (Access)			
7	Is the crew likely to have multiple competing demands on their attention?	Attention			
8	Is the crew slow in thinking, moving, monitoring, and communication?	Physical Abilities and Readiness			
	Total				
	Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Table 12-7: Team Effectiveness assessment questionnaire

Team Effectiveness					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Does the crew have limited experience in working together?	Team coordination			
2	Is there tight communication/coordination demands?	Communication availability			
3	Does the required verbal communication include similar sounding words, e.g., “increase” and “decrease”?	Communication quality			
4	Is the crew lead likely to assume that unsupervised work is sufficient (misplaced trust)?	Leadership			
5	Is the crew lead too involved in individual tasks (over focused)?	Leadership			
6	Is the crew lead overconfident?	Leadership			
7	Are the crew members non-confrontational, i.e., are they disinclined to confront nonconformance?	Team cohesion			
8	Does the crew have a cohesion problem i.e., baggage or historical issues	Team cohesion			
9	Are there crew members that are unclear about their responsibilities or duties within the group?	Role Awareness			
10	Is there a shortage of personnel required to make up the crew?	Team composition			
11	Is there a challenging mix of experience within the crew?	Team composition			
12	Is the crew lacking the training to work together?	Team training			
13	Is the required equipment (telephone, walkie-talkie, etc.) unavailable or degraded to the point that the message becomes ambiguous or interferes with communication?	Communication quality			
14	Is there excess noise in the local, ex-control room environment that degrades the quality, clarity or volume of the message?	Communication quality			
15	Are there factors (e.g.,excess noise, steam, temperature) that affect the ability of the crew to correctly obtain the required information?	Communication quality			
16	Do both the speaker and the receiver use inon-standard terminology /improper communications protocol (not using established plant communication protocols and, in particular, not using two or three way repeat-back to confirm the receipt of the correct information?	Communication quality			
	Total				
	Flag: If the answer to question 1 is Yes, then the level of the degraded state of the PIF = 0.3 + (Total no. of Yes -1)/(Total no. of Yes + No -1). Note that if (Total no. of Yes -1)/(Total no. of Yes + No -1) is greater than 0.7, it should be normalized to 0.7.				
	If the answer to questions 1 is No, then, estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Table 12-8: Bias assessment questionnaire

Bias					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Does the crew hold in their concerns instead of discussing with other?	Morale / Motivation / Attitude			
2	Does the crew lack respect for each other?	Morale / Motivation / Attitude			
3	Does the crew lack a good safety culture (indifference or bad attitude, values and belief towards safety)?	safety culture			
4	Is the crew likely to confirm the required information before proceeding to the next task?	Confidence in Information			
5	Is the cue ambiguous?	Confidence in Information			
6	Is the source of information (alarm, indicator , document, oral instructions) not trusted due to past malfunction or errors (real or perceived)?	Confidence in Information			
7	Is the crew's highly practiced response likely to interfere with the desired response?	Familiarity with or Recency of Situation			
8	Is the crew likely to misdiagnose the situation because their thinking is captivated by the initial symptoms they encountered?	Familiarity with or Recency of Situation			
9	Is the crew likely to mismatch plant responses with their prior training or experience (liek in similar and recent cases where the crew observed similar events , symptoms, or indicators, for a different cause, situation, or accident condition)?	Familiarity with or Recency of Situation			
10	Will the crew have multiple or competing goals in dealing with the current situation?	Competing or Conflicting Goals			
11	Are there competing priorities that make the correct response appear less attractive to the crew?	Competing or Conflicting Goals			
12	Is there a downside to the correct option that would bias the crew to choosing the incorrect alternative?	Bias			
13	Is there a mismatch between the procedures, policies and practice such that the correct response is biased against?	Bias			
14	Is the correct response more complicated to apply than the incorrect response?				
15	Is the correct response trained less regularly or experienced less often so that the crew would preference not to enact it when given the choice between the alternatives?	Familiarity with or Recency of Situation			
	Total				
	Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Table 12-9: Stress assessment questionnaire

Stress					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Is the crew likely to be under pressure / tensed due to their assessment of the urgency of the situation?	Stress due to situation perception			
2	Is the crew likely to be under pressure / tensed due to their assessment of the severity of the situation?	Stress due to situation perception			
3	Is the crew likely to be under pressure / tensed due to the perception that the available time is inadequate to complete the task?	Stress due to perceived sitaution urgency			
4	Is the crew likely to be under pressure / tensed due to their assessment of the magnitude of the undesired outcome or consequence of the event?	Stress due to perceived situation severity			
5	Was the crew under pressure / tensed due to their awareness of the responsibility that comes along with the particular decision they have taken?	Stress due to decision			
6	Is the crew under pressure / tensed due to their perception of the impact / consequences of their decisions on themselves, the facility and society in general?	Stress due to decision			
	Total				
	Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Table 12-10: Time Constraint assessment questionnaire

Time Constraint					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Does the task have to be completed expeditiously as opposed to a more leisurely pace with ample opportunity for checking?	Time constraint			
2	Is the crew expected to complete this task simultaneously with other assigned task?	Time constraint			
3	Is the task complex (in the sense of requiring a number of different activities within a relatively short time)?	Time constraint			
4	Does the specific scenario involve a time margin that is significantly less than those typically trained on?	Time constraint			
5	Is the timing of the scenario development such that the conditions for initiation of this action are reached before the other competing actions?	Time constraint			
6	Does the need for this response occur when other tasks or procedures are being employed (or the crew needs to respond to several things)? In other words, are multiple functions being challenged at the same time?	Time constraint			
	Total				
	Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Table 12-11: Task Load assessment questionnaire

Task Load					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Is the inherently complex nature of the problem being solved likely to induce cognitive demands on the crew?	Inherent cognitive complexity			
2	Are there external situational factors and conditions that would induce cognitive demands on the crew?	Cognitive complexity external to the mind			
3	Is the inherently complex nature of the problem being solved likely to induce physical demands on the crew?	Inherent execution complexity			
4	Are there external situational factors and conditions that would induce physical demands on the crew?	complexity external to the			
5	Are there extra work that has to be performed in addition to the main tasks e.g. making and answering phone calls while performing the task at hand?	Extra workload			
6	Is the crew presented with multiple information and cues at the same time?	Passive information load			
7	Does the task require skillful coordination of separate manipulations?	Execution complexity			
8	Are there steps which if reversed could cause a failure of the response (e.g., by damaging equipment)?	Execution complexity			
	Total				
	Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

12.3.2 Estimation of the PIF Levels

The questions provided for a specific PIF node in the quantification model aids the HRA analyst in estimating its level. This can be accomplished using the following steps (for each PIF node):

- Read through each question and if the answer is "**Yes**", place a "**Y**" in the box under the **Yes** column heading that is on the same row with the particular question. If the answer is "**No**", place an "**X**" in the box under the **No** column heading that is on the same row with the particular question. If the question is not applicable to the particular plant or setting, place a "**N/A**" in the box under the **N/A** column heading that is on the same row with the particular question.

- Add up the number of "**Y**"s, "**X**"s and "**N/A**" respectively.
- Follow the instructions given at the bottom rows of each PIF questionnaire to estimate the marginal probability level of the degraded state of that PIF.
- Input this information into marginal probability table for the PIF node in the model. Note that the sum of the marginal probabilities of both states (degraded and nominal) within the same node must be equal to 1.0. This implies that:

12.4 Methodology Steps for the BBN Model Quantification

After defining the variables to be included as nodes and the relationship between the nodes in terms of arcs, the BBN structure is considered complete. The next step is to quantify the model in order to estimate the HEP i.e., $P(CFM \cap PIF_1, PIF_2, \ldots, PIF_9)$ for each of the relevant CFMs in the model. Note that the CPTs for each of the CFMs are already populated and hence, the analyst does not need to asses or estimate their values. Therefore, the analyst needs to take the following steps in order to estimate the specific HEP:

- **Step 1: Identify the CFMs in the BBN model.** This step involves the identification of the relevant and non-relevant CFMs.
    - **Identify the relevant CFMs in the BBN model.** The BBN model contains 19 CFMs and for a particular HFE, not all of them are relevant. The relevant CFMs form the CFM cut-sets (output of the qualitative

analysis process) and need to be quantified in order to obtain the HEP. Hence, they need to be identified in the model. The other CFMs are considered "non-relevant" to the HFE and this information needs to be incorporated into the model.

  - **Identify the non-relevant CFMs in the BBN model.** Non-relevant CFMs are those that are not part of the CFM cut-set for the specific HFE. This implies that those CFMs have not occurred in the specific HFE. This is information that needs to be incorporated into the model by the analyst. This is done through the following steps:
    - Open the conditional probability tables for each of the non-relevant CFMs.
    - Change all the conditional probabilities for the failure state of each CFM to 0 (zero) i.e. all the conditional probabilities on the failure row (the 10 conditional probabilities including the leak factor).
    - Change all the conditional probabilities for the success state of each CFM to 1 (one) i.e. all the conditional probabilities on the success row (the 10 conditional probabilities including the leak factor).

- **Step 2: Identify the PIFs in the BBN model.** This step involves the identification of the relevant and non-relevant PIFs.
  - **Identify the relevant PIFs in the BBN model.** Just as in the case of CFMs, not all PIFs are relevant to the particular HFE (i.e. have an impact

on the CFMs in the specific scenario). Therefore, the “relevant PIFs” need to be identified in the model.

    - **Identify the non-relevant PIFs in the BBN model.** Non-relevant PIFs are those that ideally, do not have an impact on the CFMs in the specific scenario. This information needs to be incorporated into the model by the analyst. This is done through the following steps:
        - Open the marginal probability tables for each of the non-relevant PIFs.
        - Change all the levels for the nominal state of the PIF (marginal probability) to 1 (one).
        - Change all the levels for the degraded state of the PIF (marginal probability) to 0 (zero).
- **Step 3: Assess the PIF levels.** This step involves the assessment of the relevant PIF levels and the incorporation of the information into the model.
    - **Assess the relevant PIF levels.** Using the tables provided for each PIF in the quantification model (Table 12-3 to Table 12-11), assess the levels of the relevant PIFs by following the steps for PIF level estimation (see section 12.3.2). Note that if the analyst is uncertain about the relevance of any of the PIFs, he or she may follow these steps in estimating the PIF levels for all the PIFs. If the PIF is non-relevant, the level of its nominal state will equal 1 and that of its degraded state would equal 0. If it is relevant, the estimate of the respective levels of each PIF state will be a

number between 0 and 1, and when the level for both states of a PIF are added together, it must equal 1.

- **Input the levels of the PIFs into the model**. After determining the levels of the PIFs, these estimates need to be inputted into the model. This is done through the following steps:
    - Open the marginal probability tables for each of the PIFs.
    - Change all the levels for the nominal state of the PIF (marginal probability) to reflect the estimated probability.
    - Change all the levels for the degraded state of the PIF (marginal probability) to reflect the estimated probability.

Note that the analyst may change their assessment of the PIF levels as the go through the scenario. This information is incorporated into the BBN model in the form of evidence for that particular PIF node by either changing the levels of its states or by instantiating the PIF node to the appropriate state.

- **Step 4: Estimate the joint conditional probability of each relevant CFM**. This step involves determining the temporal ordering of the CFMs and following the proper procedure to estimate the joint conditional probability of each.
    - **Determine the temporal ordering of the CFMs.** The temporal ordering of the relevant CFMs is important in order to account for any dependencies between them. The analyst needs to know if the CFMs will be quantified with or without consideration for dependency, and the order in which they occur in the scenario of interest. If conditional independence is assumed, the analyst needs to follow the procedures for simultaneous

quantification. If dependency is considered, then the procedure for dependency quantification needs to be followed.

  - For **non-dependency quantification**, the analyst needs to take the following steps:
    - **Estimate the joint conditional probabilities of each of the relevant CFM using equation (12-4).** This is done using any of the softwares like [84], [90] - [92] which is used in constructing and quantifying BBNs. Depending on the particular software being used, the analyst needs to follow the step for running or updating the model. This information is provided in the user guide for the tool and is usually done by selecting a few tabs or clicking a few buttons on the toolbar.
  - For **dependency quantification,** see section 13.4 (Procedures for Dependency Quantification).

- **Step 5: Estimate the conditional HEP for the specific HFE.** This is the final step in the quantification process. It involves the incorporation of the joint conditional probability estimates of the relevant CFMs into the logic equation of the CFM cut-sets in order to obtain the estimated HEP for the HFE of interest.

13 HFE Dependency Modeling and Quantification

Presently, numerous HRA methods exist and new methods are still being developed. However, despite these advances made so far, many issues still exist in the field of HRA which includes the proper treatment of dependency among human failure events and hence, the corresponding human error probability (HEP) in an accident sequence. This is an ongoing issue that has been recognized and acknowledged in the HRA community, but has not been fully addressed [93].

It is recognized that in an accident sequence, early crew successes or failures can influence later crew judgments and subsequent actions. If the first action is not performed correctly, there is a high likelihood that subsequent actions will also not be performed correctly and vice versa. Therefore, dependencies among HFEs and hence, corresponding HEPs in an accident scenario should be quantitatively accounted for in the PRA model. This is particularly important so that combined probabilities are not too optimist, which could result in inappropriate decrease in the risk-significance of human actions, related accident sequences or inappropriate screening out of accident sequences from the final risk result.

13.1 Background

To a certain extent, dependency among HFEs has been considered by some HRA methods e.g. Technique for Human Error Rate Prediction (THERP) [7], Human Cognitive Reliability Model (HCR) [94], Success Likelihood Index Methodology (SLIM) [63], Accident Sequence Evaluation Program (ASEP) [95], Cause-Based Decision Tree (CBDT) [94], A Technique for Human Event Analysis (ATHEANA)

[29], and Standardized Plant Analysis Risk HRA Method (SPAR-H) [19]. However, none of these methods have adequately addressed the issue.

THERP provides a model to address dependencies among subtask within one HFE and doesn't provide explicit guidance on dependency between two or more HFEs. Also, estimates of the appropriate degree of dependency are left to the judgment of the HRA analyst and no methodology for quantification is proposed. HCR provides a conceptual discussion on dependencies that need to be addressed. However, the effect on quantification is left to the analyst judgment and no methodology is proposed. In SLIM, dependencies are expected to be addressed while defining task sequences and performance influencing factors (PIFs). However, no model or procedure is provided. ASEP uses the THERP model and therefore has the same limitations. CBDT provides a discussion on dependency but the impact on quantification and methodology is not specified. ATHEANA does not explicitly address the issue of dependency. It is discussed but no specifics are provided in terms of the modeling and quantification methodology. SPAR-H uses a THERP like dependency model with additional attributes. However, no guidance is provided to the analyst in terms of quantification. Hence, no method has provided detailed guidelines and specifics on how to model and quantify HFEs. This has contributed to the variability in results seen in the application of different HRA methods and also in cases where the same method is applied by different HRA analyst. Therefore, it is obvious that this problem has not been adequately addressed.

13.2 Overview

The application of Bayesian Belief Network (BBN) models has become increasingly popular in the field of Reliability and Risk analysis and it is gradually finding its way into the HRA domain due to its numerous benefits. The use of BBN to model HFE dependency issue was initially proposed by [6]. As part of this research work, we have proposed a full methodology for the explicit treatment of dependencies among HFEs (modeling and quantification) using the BBN model and the time slice concept of Dynamic Bayesian Networks (DBN). The methodology accounts for dynamic effects like changes in PIF levels and the ordering of HFEs during an accident scenario. It provides reproducible quantification of levels of dependency i.e. given the same inputs; the HRA analyst will obtain the same results all the time. It also provides a formal way of incorporating new information and evidence into the HEP estimation process.

The BBN model contains the specific contextual factors (PIFs) that are common between multiple HFEs and uses these dependencies to estimate the individual conditional probabilities of those HFEs and hence, the corresponding HEPs in an accident sequence. This concept of conditional dependence and independence relationships among the nodes in a BBN is being used to model dependencies between HFEs. Note that a single BBN model is used to incorporate all the HFEs and PIFs as opposed to developing an individual model for each HFE and related PIF. This is done in order to include the interdependency among the PIFs and HFEs when quantifying the BBN model.

13.2.1 Dynamic Bayesian Network

A BBN is useful for problem domains or systems where the things are static i.e. doesn't change over time. In such a system, every variable has a single and fixed value. However, this static assumption is not always the case, as many systems exist where variables are dynamic and reasoning over time is necessary, such as dynamic systems.

A Dynamic Bayesian network (DBN) is a BBN that has been extended to incorporate a temporal dimension to enable the modeling of dynamic systems [96]. The temporal extension of BBN does not mean that the network structure or parameters changes dynamically, but it means that a dynamic system is being modeled. Hence, a DBN is a directed, a-cyclic graphical model of a stochastic process. It consists of time-slices (or time-steps), with each time-slice containing its own variables. The basic idea in a DBN is to specify how variables in time t influence variables in time t+k and replicating the structure of a model for each time slice.

We are incorporating the time slice concept of the DBN into the methodology for modeling the dependency among HFEs by replicating the model structure to represent the system at each time step and then estimating the conditional probability of the relevant HFE at that particular time step.

13.3 HFE Dependency modeling and quantification methodology steps

Below are the general methodology steps [93]. Note that it is assumed that the dependency is considered in the quantification of the HFEs.

- **Step 1: Identify the variables to be included as nodes in the model**. The nodes in the model will be comprised of HFEs and PIFs.

- **Step 2: Identify the relationships between the nodes.** The relationships between the nodes are indicated using arcs with the arrowheads indicating the direction of influence. Once the HFEs, PIFs and the relationships between them are identified, the BBN structure is considered complete.
- **Step 3: Determine the number of states of the nodes.** The number of states of the node, number of parents for the node, and the number of states of the parent nodes will determine the size of the CPT for each node.
- **Step 4: Assign conditional probability table (CPT) for the nodes.** Note that each column in the CPT for any node must be equal to 1.
- **Step 5: Estimate the conditional probabilities of the HFE nodes.** This is done using any of the softwares like [84], [90] - [92] which is used in constructing and quantifying BBNs. Depending on the particular software being used, the analyst needs to follow the step for running or updating the model. This information is provided in the user guide for the tool and is usually done by selecting a few tabs or clicking a few buttons on the toolbar. The BBN now becomes the prior model before the incorporation of any new evidence.
- **Step 6: Determine the temporal ordering of the HFE nodes.** The HRA analyst needs to determine the order in which the HFEs occur in the scenario.
- **Step 7: Determine the number of temporal ordering (time-steps) of the HFE nodes.** Using the time-slice aspect of dynamic Bayesian Networks (DBN), make different copies of the BBN model as needed. The number of copies depend on the number of temporal ordering (time-steps) of the HFEs.

- **Step 8: Incorporate the relevant information into the model at each time-step.** This is known as Bayesian updating. It is done by incorporating the relevant information (evidence) into the model as it becomes available. This evidence could be in the form of newly collected data or observations about one or more HFEs or PIF levels (changes in conditional probabilities of an HFE or PIF), order of occurrence of one or more HFEs or a combination of both. This is done using any of the softwares like [84], [90] - [92] which is used in constructing and quantifying BBNs. Depending on the particular software being used, the analyst needs to follow the step for setting evidence and updating the model. This information is provided in the user guide for the tool.
- **Step 9: Estimate the conditional HEP for the given accident scenario.** This is done using the estimates obtained from step 8.

13.3.1 An Example Case

This example is used to demonstrate the application of this methodology. Note that the model and data is not real and is used only for the illustration purposes.

Consider an accident sequence which is comprised of two HFEs (HFE1 and HFE2) with three PIFs (resources, stress and training) influencing the HFEs. Stress influences both HFEs while resources and training influence HFE1 and HFE2 respectively. Therefore, in order to estimate the conditional HEP for that accident scenario, we need estimate the probability of both HFEs. Note that HFE =1 means that the human failure event has occurred. Also, the use of two HFEs is only for illustration purposes as more HFEs and PIFs can be modeled and quantified using the same methodology steps.

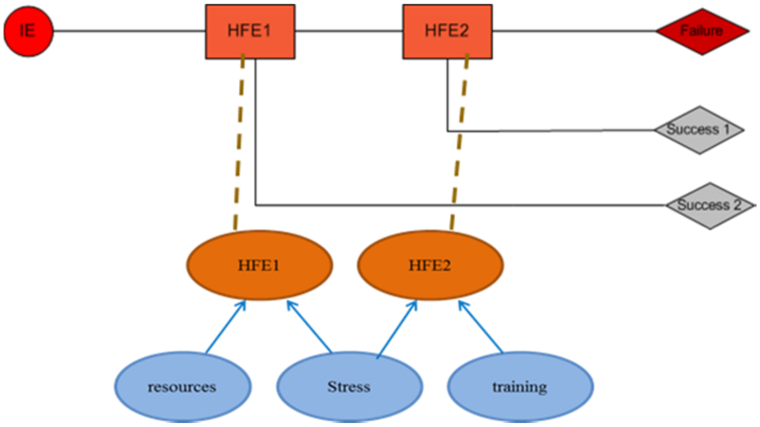


Figure 13-1: Diagram representing the example case

For the conditional independence assumption:

$$HEP = P(HFE1 = 1)\, P(HFE2 = 1) \tag{13-1}$$

However, it is assumed that the occurrence of HFE2 is dependent on HFE1 i.e. HFE1 occurs before HFE2 i.e. conditional dependency is incorporated. Hence, applying the conditional probability rule to equation (13-1) yields:

$$HEP = P(HFE1 = 1)\, P(HFE2 = 1|HFE1 = 1) \tag{13-2}$$

Using the information provided in the example case, below is the application of the methodology steps.

- **Step 1:** Variables to be included as nodes in the model are HFE1, HFE2, resources, stress and training.
- **Step 2:** This is shown in the BBN in Figure 13-1.
- **Step 3:** We assume that each node in the model has 2 states. The PIFs states are denoted as adequate and inadequate for resources and training while that of stress is denoted as high and low. The states of the HFEs are denoted as failure (occurred) and success (did not occur) respectively.

- **Step 4:** See Table 13-1 to Table 13-3. It is important to emphasize that the numbers used in this example case are for illustration purposes only and are not necessarily a reflection of the true conditional probabilities of the nodes in this model.
-

Table 13-1: Marginal probabilities for the PIFs

resources	Adequate	0.65
	Inadequate	0.35
Stress	High	0.9
	Low	0.1
training	Adequate	0.6
	Inadequate	0.4

Table 13-2: CPT for HFE1

PIFs	Resources	adequate		inadequate	
	Stress	Low	High	High	Low
HFE1	success	0.7	0.75	0.65	0.6
	Failure	0.3	0.25	0.35	0.4

Table 13-3: CPT for HFE2

PIFs	Stress	adequate		inadequate	
	Training	adequate	inadequate	adequate	inadequate
HFE1	Success	0.65	0.6	0.4	0.3
	Failure	0.35	0.4	0.6	0.7

- **Step 5:** Using the software program Trilith [84], the joint conditional probabilities of the HFEs indicated in Table 13-4.

Table 13-4: Conditional probabilities for the HFEs (results of prior model)

HFE1	success	0.684
	failure	0.316
HFE2	success	0.603
	failure	0.397

If the conditional independence assumption is made, as is the case with most other HRA methods, the conditional HEP for the accidence scenario will be given by equation (13-1), and the conditional probabilities in Table 13-4.

$$HEP = 0.316 * 0.397 = 0.125$$

- **Step 6:** HFE1 occurs before HFE2 in the accident scenario.
- **Step 7:** Two time-steps (time-step1 and time-step2) are needed to model this accident scenario. See Figure 13-2**.**

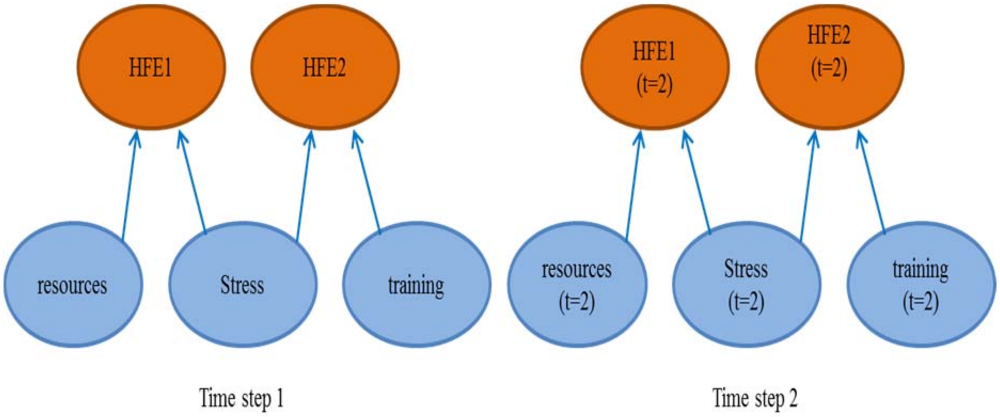


Figure 13-2: Two time-slices representing the model at two different time-steps

- **Step 8:** At time-step 1, only HFE1 has occurred in the accident scenario. Therefore, we are only concerned about HFE1 and the PIFs directly influencing it (resources and stress). We are not concerned about HFE2 (and training which influences it) since it occurs in the future. In order to incorporate this evidence into the model, all the conditional probabilities for success state of HFE2 should be set to 1 (one) i.e. all the conditional probabilities on the success row (the 4 conditional probabilities) while those for the failure state should be set to 0 (zero) i.e. all the conditional probabilities on the failure row (the 4 conditional probabilities). Also, the marginal probability for adequate state of training node should be set to 1 while that for the inadequate state should be set to 0. Thereafter, the time-step 1 model will be quantified in order to obtain the conditional probability of HFE1 i.e. P(HFE1=1) in equation (13-2). At time-step 2, the evidence that HFE1 has already occurred will be incorporated by setting the evidence for HFE1 in the model to the failure state. Thereafter, the time-step 2 model will be quantified to obtain the probability of HFE2 given the occurrence of HFE1 i.e. P(HFE2=1|HFE1=1) in equation (13-2). Refer to Table 13-5 for the condition-al probabilities of HFE1 and HFE2.

Table 13-5: Conditional probabilities for the HFEs after incorporating evidence

Time step 1 result (HFE1)	success	0.684
	failure	0.316
Time step 2 result (HFE2|HFE1)	success	0.36
	failure	0.64

- Step 9: In order to estimate the conditional HEP for accident scenario given the dependency of the HFEs, equation (13-2) is applied.

  HEP = 0.316 * 0.64 = 0.202.

Looking at this result and comparing it with the one obtained when conditional independence was (0.125), the probability of HFE2 has increased from 0.397 (when independence between the two HFEs is assumed) to 0.64 (when dependency between the two HFEs is considered). This has resulted in about a 38% increase in the HEP for the accident scenario. This is a substantial increase in the risk-significance of the accident scenario which could have been ignored if the independence assumption was applied in this analysis, or may lead to inappropriate reduction in the risk-significance of human actions and the accident scenario. As an important component of a PRA whose results are frequently used to drive risk-informed decisions, HRA results need to be consistent and should adequately address important issues like dependencies among HFEs.

13.3.2 Inclusion of additional levels of detail

Note that this methodology for dependency modeling and quantification is scalable. The BBN can be expanded to include additional levels of detail, meaning the addition of nodes as needed. This can be accomplished by adding parents to each PIF node, adding another level of nodes above the HFEs with arrows pointing from the HFEs to the new nodes or a combination of both. The incorporation of additional levels of detail in the form of parents to the PIF nodes can be very useful when conducting evidential reasoning for determining the root cause of a particular HFE. The addition of nodes above the HFE can be useful when modeling dependencies between several tasks within one HFE like the dependency model discussed in the THERP [7]. In such instances, the present HFE nodes in Figure 13-1 will become task nodes while the additional nodes then become the HFE nodes.

13.4 Procedures for Dependency Quantification

In our quantitative analysis process, the HRA analyst needs to determine the temporal ordering of the relevant CFMs in order to account for dependencies between them. The analyst needs to know if the CFMs will be quantified with or without consideration for dependency, and the order in which they occur in the scenario of interest. If dependency is considered, then dependency quantification can be accomplished through the following steps:

- **Determine the number of temporal ordering (time-steps) of the relevant CFMs.** Using the time-slice aspect of dynamic Bayesian Networks (DBN), the analyst needs to make different copies of the BBN model as needed. The number of copies depend on the number of temporal ordering (time-steps) of the relevant CFMs.
- **Incorporate the information about the relevant CFMs and PIFs into the model at each time-step.** This is known as Bayesian updating. It is done by incorporating the relevant information (evidence) into the model as it becomes available. This evidence could be in the form of newly collected data or observations about the relevant CFMs or PIF levels (changes in conditional probabilities of a relevant CFM or PIF), the order of occurrence of one or more or the relevant CFMs or a combination of both. This is done using any of the softwares like [84], [90] - [92] which is used in constructing and quantifying BBNs. Depending on the particular software being used, the analyst needs to follow the step for setting evidence for the respective nodes in the model. This information is provided in the user guide for each tool.
- **Estimate the joint conditional probabilities of each of the relevant CFM using equation (12-4).** After incorporating evidence into the model at each time step, the analyst needs to run or updating the model. This information is provided

in the user guide for the tool and is usually done by selecting a few tabs or clicking a few buttons on the toolbar.

- **Estimate the conditional HEP for the specific HFE.** This is the final step in the quantification process. It involves the incorporation of the joint conditional probability estimates of the relevant CFMs into the logic equation of the CFM cut-sets in order to obtain the estimated HEP for the HFE of interest.

14 Data Sources and Model Parameter Estimation

Many sources of information can be leveraged to estimate BBN model parameters including experimental data (e.g. simulator exercises laboratory studies), operating experience / field data (e.g. data logs, event statistics), expert opinion, HRA databases etc. Both qualitative and quantitative information can be incorporated into the model for parameter estimation.

14.1 Data sources incorporated into our BBN model

One of the major issues in the field of HRA is the availability of the required type of data for analysis. Therefore, to estimate our BBN model parameters, we had to use data from different sources since there is no single source that can provided all the information required in our model. The sources of data currently used in our model for parameter estimation include Data from other HRA methods (NARA [97] - [99], CREAM [12], SPAR-H [19], THERP [7]), expert estimates [100], [101], and operating experience [102]. We plan to incorporate data from the US NRC's HRA data program (SACADA database project) [30], [31] when it becomes available.

14.2 Model Parameters

In the previous chapters on BBN quantification, we had established that in order to estimate the joint conditional probability of each of the 19 CFMs in our BBN model (equation 12-4), we need to estimate the following model parameters:

- The marginal probabilities of both states of each of the 9 PIFs ($P(PIF_1)$, $P(PIF_2)$, …, $P(PIF_9)$. This is discussed in section 12.3 - Assessment of PIFs Levels.

- The probability of the different combinations of P(CFM_i | $PIF_1,\ldots,PIF_9$) for each of the 19 CFM. This is the data required for the CPTs for each CFM.

In this chapter, we will focus on the process of estimating the data required in populating each of the CPTs.

14.3 Conditional probability tables (CPTs) for each CFM

The CPT for each child node in the BBN (in this case each CFM) is intended to capture the strength of the relationship between each child node (CFM) and its parent nodes (PIFs). This implies that the probability of the CFM given all its possible combinations with state of PIFs needs to be defined. This can be a daunting problem as the number of cells in the CPT that need to be defined drastically increases with the addition of a parent node, parent state or child state.

Recall that for a binary node (child node) with n parents (each parent node is also binary), the number of required conditional probabilities = 2^{n+1}. Hence these probabilities grow exponentially as the number of parents increase. Now let's consider our BBN model. Each child node (CFM) has 9 parents (PIFs) and both have 2 states respectively. Therefore, to specify the strength of these relationships i.e. P(CFM_i | $PIF_1,\ldots,PIF_9$) (the CPT for each CFM), we have to define $2^{9+1} = 2^{10}$ = (1024) conditional probabilities. Also, considering the fact that we have 19 CFMs, we'll need to define a total of 1024 *19 = 19456 conditional probabilities for the CFMs in the model. This amount of data is almost impossible to manually obtain from the different data sources and this poses a very big problem in the adoption of BBN for model development.

In an attempt to address the aforementioned problem, different modeling techniques and methods could be used in simplifying the specification of a BBN. These methods which aid in reducing the number of conditional probabilities required in building CPTs and also in avoiding the manual definition of all cells in CPTs include Boolean functions (e.g. Or, And, NoisyOR etc.), and comparative expressions (e.g. THEN, IF, ELSE etc.). The adoption of any of these methods is dependent on the type of nodes defined and the situation modeled in the BBN [103].

Our BBN model consists of discrete Boolean nodes and we are modeling the impact of contextual factors (PIFs) on human performance (CFMs). In order to estimate HEP for a specific HFE, we decided to apply the NoisyOR function to aid in specifying the network and building the CPTs for the CFM nodes.

14.3.1 The NoisyOR function

The NoisyOR is a special function that can be used to specify a BBN and aid in reducing the number of cells that need to be populated when defining a CPT. It often approximates the true distribution of the conditional probabilities while also significantly reducing the effort required in building the CPTs [104]. NoisyOR function by Pearl [87] is used to describe the interactions between causal factors (causes) $X_1, X_2, \ldots, X_n$ of a condition (their common cause) Y_i. In order to apply this function, two important assumptions are being made:

- Each X_j is sufficient to cause Y_i in the absent of other causes.
- Each X_j is independent of the other in causing Y_i.

If each of the causes X_j has a probability q_{ij} of being sufficient to cause Y_i, then the Noisy-OR function allows us to populate the entire CPT of Y_i with only 2n parameters (assuming each causal factor and Y_i have binary states) instead of 2^{n+1} parameters. Therefore, the number of probabilities required for completing the CPT grows linearly rather than exponentially as the number of parents increase.

Formally, the NoisyOR function is defined as:

$$\text{NoisyOR}(X_1, q_{i1}, X_2, q_{i2}, \ldots, X_n, q_{in}) \quad \textbf{(14-1)}$$

For each ij,

$$q_{ij} = P(Y_i = \text{true} \mid X_j = \text{present}, X_k = \text{absent for each } k \neq j) \quad \textbf{(14-2)}$$

is the probability that effect Y_i will be true if cause X_j is present and all other causes X_k, $k \neq j$ are absent.

The joint conditional probability of Y_i being true, given all the causes $P(Y_i = \text{True} \mid X_1, X_2, \ldots, X_n)$ is given by:

$$1 - \prod_{j=1}^{n} \left(1 - P\left(Y_i = true \middle| X_j = true, X_k = false\ for\ each\ k \neq j\right) P(X_j = true)\right) \quad \textbf{(14-3)}$$

Extensions to the NoisyOR function have been developed such as the Recursive NoisyOR function [105] where the independent assumption of causes can be relaxed and the Leaky NoisyOR function [106] for use in situations where the effect of Y is true even when all the causes $X_1, X_2, \ldots, X_n$ are absent.

14.3.2 Leaky NoisyOR Function

This is an extension of the NoisyOR function to incorporate a parameter $\boldsymbol{l_i}$ called the leak factor. The leak factor is the probability that Y_i will be true when all the causes are absent. In other words, its value represents the combined effect of all causes of Y_i that are not explicitly indicated in the model:

$$l_i = \mathrm{P}(\mathrm{Y_i} = \mathrm{true} \mid \mathrm{X_1} = \mathrm{absent}, \mathrm{X_2} = \mathrm{absent}, \ldots, \mathrm{X_n} = \mathrm{absent}) \quad \text{(14-4)}$$

For the Leaky NoisyOR function, the joint conditional probability of Y_i being true, given all the causes $P(Y_i = True \mid X_1, X_2, \ldots, X_n)$ is given by:

$$1 - \prod_{j=1}^{n} \left[1 - P\left(Y_i = true \middle| X_j = true, X_k = false\ for\ each\ k \neq j\right) P(X_j = true)\right] P(1 - l_i) \quad \text{(14-5)}$$

In relation to our BBN quantification model, the Leaky NoisyOR function is more appealing because we can represent the residual effect of the CFM i.e. the probability that a crew failure has occurred even when there is no influence from any of the PIFs. Hence, it gives us a way to account for other influencing factors that are not explicitly represented in the BBN model as individual PIF nodes.

With the application of the Leaky NoisyOR function, the number of conditional probabilities required for populating the CPTs for each CFM i.e. different combinations of $P(CFM_i \mid PIF_1, \ldots, PIF_9)$, which was 1024 reduces to $2(n+1) = 20$. Specifically, the following conditional probabilities are required to populate our CPT:

- $P(CFM_i = failure \mid PIF_j = degraded, PIF_k = nominal\ for\ each\ k \neq j)$. This is the conditional probability that a crew failure has occurred given that a particular PIF is in the degraded state (i.e. the PIF has a negative influence on the CFM) and the other PIFs are nominal (i.e. they have no influence on the CFM). It represents the independent influence of a particular PIF on a CFM. This probability = $\boldsymbol{q_{ij}}$ (equation 14-2).
- $P(CFM_i = success \mid PIF_j = degraded, PIF_k = nominal\ for\ each\ k \neq j)$. This is the conditional probability that a crew failure has not occurred given that a particular

PIF is in the degraded state and the other PIFs are in the nominal state. Note that this probability = 1 - $\boldsymbol{q_{ij}}$.

- P(CFM_i = failure | PIF_1 = nominal ,..., PIF_9 = nominal). This is the conditional probability that a crew failure has occurred given that all the PIFs are in the nominal state. This probability represents the leak factor ($\boldsymbol{l_i}$) i.e. other influencing factors that have not been explicitly represented in the model. This implies that leak factor is the probability that a crew failure has occurred even when there is no influence from any of the PIFs in the model.
- P(CFM_i = success | PIF_1 = nominal ,..., PIF_9 = nominal). This is the conditional probability that a crew failure has not occurred given that all the PIFs are in the nominal state. This probability = 1 – $\boldsymbol{l_i}$.

Therefore, to populate the CPT for each CFM, we need $\boldsymbol{q_{ij}}$ for each PIF in the model and $\boldsymbol{l_i}$ for each CFM. Also, $\boldsymbol{l_i}$ and $\boldsymbol{q_{ij}}$ are related through a multiplier ($\boldsymbol{r_j}$). Therefore,

$$\boldsymbol{r_j = \frac{q_{ij}}{l_i}} \quad (14\text{-}6)$$

The multiplier, $\boldsymbol{r_j}$, is a number used to indicate the individual influence of a PIF on a CFM. The multiplier “1” implies that the PIF has no influence on the CFM i.e. it doesn’t change the conditional probability of the CFM. Any number greater than 1 implies that the PIF has an influence on the CFM and the larger the number, the greater the influence.

14.4 Data Gathering from the sources

This process involved the review of each data source previously indicated in this chapter to determine if it has any data or information that can be mapped to any of the three parameters (l_i, q_{ij} and r_j) required by our model. The data sources we selected cover a diverse spectrum including; first and second generation HRA methods, HEP estimates generated by experts for task in US NPPs, data estimated from NPP operational records in Germany, and an HRA database (future data source) which is currently being developed by the US NRC. Also, each of the HRA methods generated their data from other HRA methods and available databases.

14.4.1 Nuclear Action Reliability Assessment (NARA) HRA Method

NARA [97]-[99] is one of the first generation HRA methods that were developed as a refinement of HEART (Human Error Assessment and Reduction Technique) HRA method [35], [36]. NARA uses the same approach as HEART to estimate HEPs. However, the main differences between NARA and HEART are the grouping of the generic tasks, the weights of the error producing contexts (EPCs) and the use of CORE-DATA human error database (containing data from various industries including nuclear, oil & gas, manufacturing, power transmission etc.) in NARA for estimating the generic task types (GTTs) [107]. It was due to these reasons that we decided to use NARA as one of our data sources.

We mapped NARA's GGTs (Table C1) to our CFMs and the EPCs (Table C2) to our PIFs respectively (Table 14-1). This was done in order to use the estimates of both parameters from NARA in estimating our model parameters. Note that the HEPs of the GGTs are used in estimating parameter l_i (leak factor). This is because since the description of each GGT is given without any reference to possible influencing factor, we assumed that the estimates were done assuming that all the PIFs (which would map directly to our model) were nominal. Also, the EPC Affects are used in estimating parameter $\boldsymbol{r_j}$ (multiplier) in our model. Here is a list of our Main PIFs and their respective ID numbers: HSI = 1, Procedures = 2, Resources = 3, Team Effectiveness = 4, Knowledge / Abilities = 5, Bias = 6, Stress = 7, Task load = 8, Time constraint = 9. For the CFMs and the respective IDs, see Table 7-1.

Table 14-1: Mapping of GGTs and EPCs to CFMs and PIFs

NARA's GGT			Our CFM ID	NARA's EPC		Our Main PIF Groups
ID	HEP	95% t-confidence	ID	ID	Affect	ID
A1	5.00E-03	2.0E-03 - 1.0E-02	A2	1	24	8
A2	1.00E-03	n/a (only 3 data points)	D2 or D4 or D5 or A2	2	20	none
A3	2.00E-03	7.0E-04 - 6.0E-03	D4 or D5 or A2	3	11	8 or 9
A4	6.00E-03	n/a (only 3 data points)	D1 or D2 or D7	4	10	none
A5	1.00E-04	4.0E-06 - 2.0E-03	none	5	10	none
B1	2.00E-02	3.0E-03 - 2.0E-01	I9	6	10	4
B2	4.00E-03	8.0E-04 - 2.0E-02	D4 or D5 or A2	7	9	none
B3	7.00E-04	n/a (only 3 data points)	D4 or A2	8	9	none
B4	3.00E-03	3.0E-04 - 3.0E-02	D2 or D4 or A2	9	8	5
B5	3.00E-02	n/a (only 1 data points)	I5	10	6	1
C1	4.00E-04	n/a (only 1 data points)	I1	11	4	1
C2	2.00E-01	15.0E-02 - 33.0E-02	D1	12	3	2
D1	6.00E-03	2.0E-03 - 9.0E-03	I7	13	3	none
				14	2.5	6
				15	2	2
				16	8	3
				17	2	none
				18	2	7
				19	2	6

Though we attempted to map the GGTs to our CFMs (except A5 because we didn't find a match), we were only able to include the GGTs that were mapped to a single CFM in our estimate of parameter $\boldsymbol{l_i}$. This is because the linear equations which resulted from the GGTs that were mapped to more than one of our CFMs didn't produce consistent results when solved. Also, we couldn't obtain estimates of all the GGTs in the equations. Hence, we didn't include the following GGTs in our final estimate of $\boldsymbol{l_i}$: A2, A3, A4, B2, B3, and B4.

For the EPCs, we only include the ones that mapped to our PIFs (except EPC- 3 which maps to two of our PIFs) in our estimate of $\boldsymbol{r_j}$. Note that as a general rule in our data gathering process, we excluded any data point (from any data source) that is made up of more than one data point in our model e.g. NARA's GGT (A2) which is a made up of CFMs D2, D4, D5 and A2 (i.e. NARA's A2 is $\cong$ D2+D4+D5+A2). This was done in order to avoid the resulting inconsistencies when we attempted to estimate each of the data points it maps to (in our model).

14.4.2 Standardized Plant Analysis Risk HRA (SPAR-H) Method

SPAR-H [19] is one of the second generation methods that were developed for the US NRC in order to estimate HEPs for use in SPAR PRA models of US nuclear power plants (NPPs). It is one of the most widely applied HRA methods and has been used as part of PRA in over 70 US NPPs. It was originally developed as a screening methodology, but was later extended for full HRP estimation.

SPAR-H has 8 PIFs and multipliers for both diagnosis and action task (Table C3) which we have mapped to our PIFs (see Table 14-2). For simplicity, we have used the following identification numbers (IDs) for the SPAR-H PIFs; Available time = 1, Stressors = 2, Complexity = 3, Experience / Training = 4, procedures = 5, Ergonomics = 6, Fitness for duty = 7, and Work processes = 8. Note that we are interested in multipliers greater than 1 since those have a negative influence on human performance i.e. degrade it. The multipliers from SPAR-H are used in estimating parameter r_j (multiplier) in our model. Note that data from SPAR-H PIF 8 was excluded from our final estimate of parameter r_j.

Table 14-2: Mapping of SPAR-H PIFs to our model PIFs

SPAR-H's PIF and Multiplier							Our Main PIF Groups
ID	Diagnosis levels			Action levels			ID
1	10			10			9
2	2	5		2	5		7
3	2	5		2	5		8
4	10			3			5
5	5	20	50	5	20	50	2
6	10	50		10	50		1
7	5			5			5
8	2			5			3 or 4 or 6

14.4.3 Cognitive Reliability and Error Analysis Method (CREAM)

CREAM [12] is a second generation HRA method that was developed for general applications, based on the Contextual Control Model [108]. From the information processing perspective, CREAM has emphasized the identification and estimation of cognitive errors. According to [32], this method has been used in two recent NASA PRAs.

CREAM has generic failure types (Table C4) which we mapped to our CFMs and common performance conditions (CPCs) (Table C5) which we mapped to our PIFs (Table 14-3). The basic values of the generic failure types are used in estimating parameter l_i (leak factor). This is because since each generic failure type is given without any reference to a direct possible influencing factor, we assumed that the estimates were done assuming that all the PIFs (which would map directly to our model) were nominal. Also, the weighting factors for the CPCs shown as COCOM function in (Table C5), are used in estimating parameter $\boldsymbol{r_j}$ (multiplier) in our model. We have used the following identification numbers (IDs) for the CREAM CPCs; Adequacy of organisation = 1, Working conditions = 2, Adequacy of MMI and operational support = 3, Availability of procedures / plans = 4, Number of simultaneous goals = 5, Available time = 6, Time of day = 7, Adequacy of training and preparation = 8, and crew collaboration quality = 9. We are interested in multipliers greater than 1 since those have a negative influence on human performance i.e. degrade it.

Table 14-3: Mapping of generic failure types and CPCs to CFMs and PIFs

CREAM's Generic failure type			Our CFM ID	CREAM's CPC					Our Main PIF Groups
					Multiplier				
ID	Basic value	90% confidence bounds	ID	ID	obs	int	plan	exe	ID
O1	1.00E-03	3.0E-04 - 3.0E-03	I6, I8	1	1	1	2	2	3 or 4 or 6
O2	7.00E-02	2.0E-02 - 17.0E-02	I5	2	2	2	1	2	3
O3	7.00E-02	2.0E-02 - 17.0E-02	I1, I2, I3, I4	3	5	1	1	5	1
I1	2.00E-01	9.0E-02 - 6.0E-01	D1	4	2	1	5	2	2
I2	1.00E-02	1.0E-03 - 1.0E-01	I4, D4, D5, D6, D7	5	2	2	5	2	6
I3	1.00E-02	1.0E-03 - 1.0E-01	I5, D6	6	5	5	5	5	9
P1	1.00E-02	1.0E-03 - 1.0E-01	D3, D7	7	1.2	1.2	1.2	1.2	5
P2	1.00E-02	1.0E-03 - 1.0E-01	D3, D7	8	2	5	5	2	5
E1	3.00E-03	1.0E-03 - 9.0E-03	A2	9	2	2	2	5	4
E2	3.00E-03	1.0E-03 - 9.0E-03	A1						
E3	5.00E-04	5.0E-05 - 5.0E-03	A3						
E4	3.00E-03	1.0E-03 - 9.0E-03	A2						
E5	3.00E-02	25.0E-03 - 4.0E-02	A2						

We were able to map all the generic failure types to our CFMs and included all the basic values in our estimate of parameter $\boldsymbol{l_i}$. Note that the mapping of a generic failure type to more than one CFM e.g. O1 maps to CFMs I6 and I8 implies that O1 could be I6 or I8 and this is very different from a situation where O1 could be made up of I6 and I8 i.e. I6 or I8 (as in the case of some NARA GGTs and SPAR-H PIF which have been excluded from the estimates).

The data from CPC 1 was excluded from our final estimate of parameter r_j due to the aforementioned reasons. The CPC multipliers are divided into 4 groups namely observation (obs), interpretation (int), planning (plan), and execution (exe). These groups are mapped to the phases of our cognitive model as follows; obs and int = I (information processing) phase, int and plan = D (decision making) phase, and exe = A (Action) phase. These mappings are reflected in our estimate of r_j.

14.4.4 German Nuclear Power Plant (NPP) operating experience data

The first systematic attempt to generate human reliability data from German NPP was recently published in [102]. According to [102], the data was collected and analyzed in a transparent and traceable manner, and is not specific to any particular HRA method. The results were also compared with the data obtained in the THERP handbook [7]. Hence, we decided to use it as one of our data sources.

We mapped the samples (errors) that were analyzed (Table C6) to our CFMs and PIFs in terms of parameters l_i and q_{ij} in our model (Table 14-4). Note that some error descriptions that were given had influencing factors that did not directly map to any of our PIFs and hence, we mapped those to l_i. Those that had influencing factors that mapped directly to our PIFs were mapped q_{ij}. In instances where more than one influencing factor was reported as relevant to the error, we had to use our judgment in determining the more dominant PIF in order to determine the particular q_{ij} to map it to. Some errors from Table C6 (ID numbers 24, 25, 26 and 36) were excluded from our parameter estimates because according to [102], the samples were considered too small to be of statistical significance.

Table 14-4: Mapping of German NPP HEP estimates to our model parameters

German NPP				THERP	Our Model		
ID	HEP estimate	90% confidence bounds		HEP estimate	CFMs	PIFs	Parameter
1	1.20E-03	1.80E-04	4.00E-03	0.001	A3	1	q_{A31}
2	1.30E-03	1.90E-04	4.00E-03	none	A2	8	q_{A28}
3	3.50E-03	9.00E-04	9.00E-03	none	A1	9	q_{A19}
4	2.40E-02	3.60E-03	7.80E-02	none	A3	1	q_{A31}
5	8.90E-04	1.30E-04	2.90E-03	0.003	A3	1	q_{A31}
6	2.90E-03	4.40E-04	9.70E-03	0.0005	A3	1	q_{A31}
7	7.80E-04	1.20E-04	2.60E-03	none	A3	6	q_{A36}
8	2.70E-03	4.00E-04	8.80E-03	0.001	A3	1	q_{A31}
9	1.00E-03	1.50E-04	3.40E-03	0.003	A3	1	q_{A31}
10	1.50E-02	2.20E-03	4.70E-02	none	A1	7	q_{A17}
11	6.90E-03	1.00E-03	2.30E-02	0.0005	A3	1	q_{A31}
12	9.80E-04	1.50E-04	3.30E-03	none	A2	1	q_{A21}
13	7.80E-03	1.20E-03	2.50E-02	0.003	A3	1	q_{A31}
14	7.90E-04	1.20E-04	2.60E-03	0.003	A1	none	l_{A1}
15	4.20E-02	6.30E-03	1.30E-01	none	A2	7	q_{A27}
16	3.30E-02	4.90E-03	1.00E-01	none	D7	5	q_{D75}
17	3.50E-02	5.40E-03	1.10E-01	none	D7	5	q_{D75}
18	1.40E-02	2.10E-03	4.60E-02	none	D7	5	q_{D75}
19	1.30E-03	1.90E-04	4.40E-03	none	D7	1	q_{D71}
20	6.50E-02	9.90E-03	2.00E-01	none	D7	5	q_{D75}
21	6.80E-02	1.00E-02	2.10E-01	none	D1	7	q_{D17}
22	5.00E-01	1.70E-01	8.30E-01	none	D7	5	q_{D75}
23	2.10E-02	3.20E-03	6.80E-02	none	A2	5	q_{A25}
24	9.50E-01	6.40E-01	1.00E+00	none	I5	1	q_{I51}
25	9.50E-01	6.40E-01	1.00E+00	none	I5	4	q_{I54}
26	8.40E-01	2.30E-01	9.90E-01	none	I6	none	l_{I6}
27	2.40E-02	3.50E-03	7.60E-02	0.01	D7	5	q_{D75}
28	1.60E-01	2.60E-02	4.40E-02	0.1	D7	5	q_{D75}
29	5.60E-03	8.30E-04	1.80E-02	0.003	I6	2	q_{I62}
30	8.00E-04	1.20E-04	2.70E-03	none	D7	5	q_{D75}
31	4.20E-02	6.30E-03	1.30E-01	none	D7	5	q_{D75}
32	1.20E-02	3.20E-03	3.00E-02	0.006	I6	7	q_{I67}
33	2.70E-03	4.00E-04	8.80E-03	0.003	I6	2	q_{I62}
34	5.80E-02	8.90E-03	1.80E-01	none	D7	5	q_{D75}
35	2.40E-02	3.70E-03	7.90E-02	none	D7	5	q_{D75}
36	8.40E-01	2.30E-01	9.90E-01	none	D7	2	q_{D72}
37	2.90E-02	4.40E-03	9.40E-02	none	D2	2	q_{D72}

14.4.5 HEP estimates generated by experts for tasks in US NPPs

As part of a research program that was conducted by the US NRC to determine the practicality and usefulness of several methods for obtaining human reliability data and estimates for inclusion in NPP PRAs, expert judgment was used to generate HEP estimates and associated uncertainty bounds [100], [101]. These estimates were generated using paired comparisons and direct numerical estimation techniques. They correspond to two separate task list (level 1 tasks and levels 2 &3 tasks) tailored specifically for boiling water reactors.

We mapped both level 1 and 2&3 tasks, and estimates generated using the direct numerical estimation technique (Table C7 & Table C8) as recommended by the authors to our CFMs and PIFs, in terms of parameters $\boldsymbol{l_i}$ and $\boldsymbol{q_{ij}}$ in our model (Table 14-5). Note that some tasks descriptions contained information on influencing factors that directly map to any of our PIFs and hence, we mapped those to $\boldsymbol{q_{ij}}$. Those that did not have influencing factors that mapped directly to our PIFs were mapped $\boldsymbol{l_i}$. Also, we included "T" as a part of the ID number for levels 2 & 3 tasks in order to differentiate them from level 1 tasks. Task ID "5" couldn't be mapped to any of our parameters and we also excluded data from task IDs 4, 9, 10, 11, 14, 15 and T15 from our parameter estimates due to reasons discussed in previous sections in this chapter.

Table 14-5: Mapping of expert generated HEP estimates to our model parameters

Expert Estimates				Our Model		
ID	**HEP estimate**	**Uncertainty bounds**		**CFMs**	**PIFs**	**Parameter**
1	7.00E-04	6.00E-05	8.00E-03	A1	none	l_{A1}
2	1.00E-03	2.00E-04	6.00E-03	A2	none	l_{A2}
3	8.00E-04	7.00E-05	9.00E-03	A2	none	l_{A2}
4	2.00E-04	2.00E-05	3.00E-03	D2 or D4 or D5	none	***none***
5	2.00E-04	3.00E-05	1.00E-03	none	none	***none***
6	7.00E-02	7.00E-03	3.10E-01	D1	5	q_{D15}
7	6.00E-03	2.00E-04	3.00E-02	D2	none	l_{D2}
8	4.00E-02	5.00E-03	3.00E-01	D3	none	l_{D3}
9	1.00E-04	2.00E-05	2.00E-03	D5 or A1	none	***none***
10	1.00E-02	1.00E-03	2.00E-01	D5 or A2	none	***none***
11	3.00E-04	2.00E-05	2.00E-03	D5 or A2	none	***none***
12	1.00E-03	9.00E-05	3.00E-02	D2	none	l_{D2}
13	2.00E-03	1.00E-04	2.00E-02	D1	none	l_{D1}
14	5.00E-04	4.00E-05	3.00E-03	D6 or A1	none	***none***
15	3.00E-02	5.00E-03	3.90E-01	D6 or A1	none	***none***
T1	4.00E-03	6.00E-04	3.00E-02	A3	1	q_{A31}
T2	2.00E-03	3.00E-04	1.00E-02	A3	1	q_{A31}
T3	5.00E-04	1.00E-04	3.00E-03	A3	1	q_{A31}
T4	5.00E-04	8.00E-05	4.00E-03	A2	1	q_{A21}
T5	2.00E-02	2.00E-03	2.60E-01	A3	1	q_{A31}
T6	4.00E-04	4.00E-05	3.00E-03	A3	none	l_{A3}
T7	1.00E-03	9.00E-05	1.00E-02	I6	1	q_{I61}
T8	6.00E-03	6.00E-04	3.00E-02	I6	1	q_{I61}
T9	1.00E-02	1.00E-03	5.00E-02	I6	1	q_{I61}
T10	3.00E-03	2.00E-04	2.00E-02	A3	1	q_{A31}
T11	3.00E-03	2.00E-04	4.00E-02	I6	none	l_{I6}
T12	2.00E-02	2.00E-03	1.00E-01	I1	none	l_{I1}
T13	7.00E-03	5.00E-04	3.00E-02	I6	none	l_{I6}
T14	2.00E-06	4.00E-07	9.00E-06	I1	none	l_{I1}
T15	4.00E-02	3.00E-03	2.90E-01	I1 or I2 or I4	none	***none***
T16	5.00E-05	9.00E-06	3.00E-04	I6	none	l_{I6}
T17	1.00E-03	1.00E-04	8.00E-03	I5	none	l_{I5}
T18	1.00E-02	1.00E-03	4.00E-02	I5	1	q_{I51}
T19	3.00E-03	1.00E-03	8.00E-02	I5	none	l_{I5}
T20	3.00E-03	5.00E-04	2.00E-02	A2	none	l_{A2}

14.4.6 Summary of Data Gathered

We have organized the data gathered from the different sources into tables in order to clearly indicate what is being used in estimating each of our model parameters $\boldsymbol{l_i}$, $\boldsymbol{r_j}$ and $\boldsymbol{q_{ij}}$.

14.4.6.1 Data and sources used in estimating parameter l_i

As a reminder, $\boldsymbol{l_i}$ represents the leak factor i.e. P(CFM$_i$ = failure | PIF$_1$ = nominal ,..., PIF$_9$ = nominal). This is the conditional probability that a crew failure has occurred even when there is no influence from any of the PIFs. Therefore, it represents other influencing factors that have not been explicitly represented in the model. The data gathered and used in estimating this parameter is indicated in Table 14-6.

14.4.6.2 Data and sources used in estimating parameter q_{ij}

Note that $\boldsymbol{q_{ij}}$ represents P(CFM$_i$ = failure | PIF$_j$ = degraded, PIF$_k$ = nominal for each $k \neq j$). This is the conditional probability that a crew failure has occurred given that a particular PIF is in the degraded state (i.e. the PIF has a negative influence on the CFM) and the other PIFs are nominal (i.e. they have no influence on the CFM). The data gathered and used in estimating this parameter is indicated in Table 14-7.

Table 14-6: Summary of data gathered for estimating parameter l_i

ID	CFM	NARA			CREAM			German NPP			THERP	Expert Estimates			
		ID	Value	95% t-confidence	ID	Value	Bounds (90% confidence)	ID	HEP	Bounds (90% confidence)		ID	HEP	LB	UB
I1	Key Alarm not Responded to (intentional & unintentional)	C1	4.00E-04	N/A - only 1 data point	O3	7.00E-02	2.0E-02 - 17.0E-02					T12	2.00E-02	2.00E-03	1.00E-01
												T14	0.000002	0.0000004	9.00E-06
I2	Data Not Obtained (Intentional)				O3	7.00E-02	2.0E-02 - 17.0E-02								
I3	Data Discounted				O3	7.00E-02	2.0E-02 - 17.0E-02								
I4	Decision to Stop Gathering Data				O3	7.00E-02	2.0E-02 - 17.0E-02								
					I2	1.00E-02	1.0E-03 -1.0E-01								
I5	Data Incorrectly Processed	B5	3.00E-02	N/A - only 1 data point	O2	7.00E-02	2.0E-02 - 17.0E-02					T17	1.00E-03	1.00E-04	8.00E-03
					I3	1.00E-02	1.0E-03 -1.0E-01					T19	3.00E-03	1.00E-03	8.00E-02
I6	Reading Error				O1	1.00E-03	3.0E-04 - 3.0E-03					T11	3.00E-03	2.00E-04	4.00E-02
												T13	7.00E-03	5.00E-04	3.00E-02
												T16	5.00E-05	9.00E-06	3.00E-04
I7	Information Miscommunicated	D1	6.00E-03	2.00E-03 - 9.00E-03											
I8	Wrong Data Source Attended to				O1	1.00E-03	3.0E-04 - 3.0E-03								
I9	Data Not Checked with Appropriate Frequency	B1	2.00E-02	3.0E-03 - 2.0E-01											
D1	Plant/System State Misdiagnosed	C2	2.00E-01	15.0E-02 - 33.0E-02	I1	2.00E-01	9.0E-02 - 6.0E-01					13	2.00E-03	1.00E-04	2.00E-02
D2	Procedure Misinterpreted											7	6.00E-03	2.00E-04	3.00E-02
												12	1.00E-03	9.00E-05	3.00E-02
D3	Failure to adapt procedures to the situation				P1	1.00E-02	1.0E-03 -1.0E-01					8	4.00E-02	5.00E-03	3.00E-01
					P2	1.00E-02	1.0E-03 -1.0E-01								
D4	Procedure Step Omitted (Intentional)				I2	1.00E-02	1.0E-03 -1.0E-01								
D5	Inappropriate Transfer to a Different Procedure				I2	1.00E-02	1.0E-03 -1.0E-01								
D6	Decision to Delay Action				I2	1.00E-02	1.0E-03 -1.0E-01								
					I3	1.00E-02	1.0E-03 -1.0E-01								
D7	Inappropriate Strategy Chosen				I2	1.00E-02	1.0E-03 -1.0E-01								
					P1	1.00E-02	1.0E-03 -1.0E-01								
					P2	1.00E-02	1.0E-03 -1.0E-01								
A1	Incorrect Timing				E2	3.00E-03	1.0E-03 - 9.0E-03	14	7.90E-04	12.0E-05 - 26.0E-04	3.00E-03	1	7.00E-04	6.00E-05	8.00E-03
A2	Incorrect Operation of Component/Object	A1	5.00E-03	2.0E-03 - 1.0E-02	E1	3.00E-03	1.0E-03 - 9.0E-03					2	1.00E-03	2.00E-04	6.00E-03
					E4	3.00E-03	1.0E-03 - 9.0E-03					3	8.00E-04	7.00E-05	9.00E-03
					E5	3.00E-02	25.0E-03 - 4.0E-02					T20	3.00E-03	5.00E-04	2.00E-02
A3	Action on Wrong Component / object				E3	5.00E-04	5.0E-05 - 5.0E-03					T6	4.00E-04	4.00E-05	3.00E-03

Table 14-7: Summary of data gathered for estimating parameter q_{ij}

CFMs and IDs		PIFs																					
		HSI					Procedures			Knowledge / Abilities					Bias		Stress			Task Load		Time Constraint	
		German NPP		THERP	Expert estimates		German NPP		THERP	German NPP		THERP	Expert estimates		German NPP		German NPP		THERP	German NPP		German NPP	
ID	CFMs	ID	HEP	HEP	ID	HEP	ID	HEP	HEP	ID	HEP	HEP	ID	HEP	ID	HEP	ID	HEP	HEP	ID	HEP	ID	HEP
I5	Data Incorrectly Processed				T18	1.00E-02																	
I6	Reading Error				T7	1.00E-03	29	5.60E-03	3.00E-03								32	1.20E-02	6.00E-03				
					T8	6.00E-03	33	2.70E-03	3.00E-03														
					T9	1.00E-02																	
D1	Plant/System State Misdiagnosed												6	7.00E-02			21	6.80E-02					
D2	Procedure Misinterpreted						37	2.90E-02															
D7	Inappropriate Strategy Chosen	19	1.30E-03							16	3.30E-02												
										17	3.50E-02												
										18	1.40E-02												
										20	6.50E-02												
										22	5.00E-01												
										27	2.40E-02	1.00E-02											
										28	1.60E-01	1.00E-01											
										30	8.00E-04												
										31	4.20E-02												
										34	5.80E-02												
										35	2.40E-02												
A1	Incorrect Timing																10	1.50E-02				3	3.50E-03
A2	Incorrect Operation of Component/Object	12	9.80E-04		T4	5.00E-04				23	2.10E-02						15	4.20E-02		2	1.30E-03		
A3	Action on Wrong Component / object	1	1.20E-03	1.00E-03	T1	4.00E-03									7	7.80E-04							
		4	2.40E-02		T2	2.00E-03																	
		5	8.90E-04	3.00E-03	T3	5.00E-04																	
		6	2.90E-03	5.00E-04	T5	2.00E-02																	
		8	2.70E-03	1.00E-03	T10	3.00E-03																	
		9	1.00E-03	3.00E-03																			
		11	6.90E-03	5.00E-04																			
		13	7.80E-03	3.00E-03																			

Table 14-8: Summary of data gathered for estimating parameter r_j (PIFs 1-3)

CFMs and ID		HSI										PROCEDURES											RESOURCES						
		NARA				SPAR-H			CREAM			NARA				SPAR-H				CREAM			NARA		SPAR-H		CREAM		
ID	CFMs	ID	Xplier	ID	Xplier	ID	Xplier		ID	Xplier		ID	Xplier	ID	Xplier	ID	Xplier			ID	Xplier		ID	Xplier	ID	Xplier	ID	Xplier	Xplier
I1	Key Alarm not Responded to (intentional & unintentional)	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
I2	Data Not Obtained (Intentional)	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
I3	Data Discounted	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
I4	Decision to Stop Gathering Data	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
I5	Data Incorrectly Processed	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
I6	Reading Error	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
I7	Information Miscommunicated	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
I8	Wrong Data Source Attended to	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
I9	Data Not Checked with Appropriate Frequency	10	**6**	11	**4**	6	**10**	**50**	3	**5**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**	**1**	16	**8**			2	**2**	**2**
D1	Plant/System State Misdiagnosed	10	**6**	11	**4**	6	**10**	**50**	3	**1**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**1**	**5**	16	**8**			2	**2**	**1**
D2	Procedure Misinterpreted	10	**6**	11	**4**	6	**10**	**50**	3	**1**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**1**	**5**	16	**8**			2	**2**	**1**
D3	Failure to adapt procedures to the	10	**6**	11	**4**	6	**10**	**50**	3	**1**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**1**	**5**	16	**8**			2	**2**	**1**
D4	Procedure Step Omitted (Intentional)	10	**6**	11	**4**	6	**10**	**50**	3	**1**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**1**	**5**	16	**8**			2	**2**	**1**
D5	Inappropriate Transfer to a Different Procedure	10	**6**	11	**4**	6	**10**	**50**	3	**1**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**1**	**5**	16	**8**			2	**2**	**1**
D6	Decision to Delay Action	10	**6**	11	**4**	6	**10**	**50**	3	**1**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**1**	**5**	16	**8**			2	**2**	**1**
D7	Inappropriate Strategy Chosen	10	**6**	11	**4**	6	**10**	**50**	3	**1**	**1**	12	**3**	15	**2**	5	**5**	**20**	**50**	4	**1**	**5**	16	**8**			2	**2**	**1**
A1	Incorrect Timing	10	**6**	11	**4**	6	**10**	**50**	3	**5**		12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**		16	**8**			2	**2**	
A2	Incorrect Operation of Component/Object	10	**6**	11	**4**	6	**10**	**50**	3	**5**		12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**		16	**8**			2	**2**	
A3	Action on Wrong Component / object	10	**6**	11	**4**	6	**10**	**50**	3	**5**		12	**3**	15	**2**	5	**5**	**20**	**50**	4	**2**		16	**8**			2	**2**	

Table 14-9: Summary of data gathered for estimating parameter r_j (PIFs 4-6)

CFMs and ID		TEAM EFFECTIVENESS							KNOWLEDGE / ABILITIES												BIAS								
		NARA		SPAR-H		CREAM			NARA		SPAR-H				CREAM						NARA				SPAR-H		CREAM		
ID	CFMs	ID	Xplier	ID	Xplier	ID	Xplier	Xplier	ID	Xplier	ID	Xplier	ID	Xplier	ID	Xplier	Xplier	ID	Xplier	Xplier	ID	Xplier	ID	Xplier	ID	Xplier	ID	Xplier	Xplier
I1	Key Alarm not Responded to (intentional & unintentional)	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
I2	Data Not Obtained (Intentional)	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
I3	Data Discounted	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
I4	Decision to Stop Gathering Data	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
I5	Data Incorrectly Processed	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
I6	Reading Error	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
I7	Information Miscommunicated	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
I8	Wrong Data Source Attended to	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
I9	Data Not Checked with Appropriate Frequency	6	**10**			9	**2**	**2**	9	**8**	4	**3**	7	**5**	7	**1.2**	**1.2**	8	**2**	**5**	14	**2.5**	19	**2**			5	**2**	**2**
D1	Plant/System State Misdiagnosed	6	**10**			9	**2**	**2**	9	**8**	4	**10**	7	**5**	7	**1.2**	**1.2**	8	**5**	**5**	14	**2.5**	19	**2**			5	**2**	**5**
D2	Procedure Misinterpreted	6	**10**			9	**2**	**2**	9	**8**	4	**10**	7	**5**	7	**1.2**	**1.2**	8	**5**	**5**	14	**2.5**	19	**2**			5	**2**	**5**
D3	Failure to adapt procedures to the situation	6	**10**			9	**2**	**2**	9	**8**	4	**10**	7	**5**	7	**1.2**	**1.2**	8	**5**	**5**	14	**2.5**	19	**2**			5	**2**	**5**
D4	Procedure Step Omitted (Intentional)	6	**10**			9	**2**	**2**	9	**8**	4	**10**	7	**5**	7	**1.2**	**1.2**	8	**5**	**5**	14	**2.5**	19	**2**			5	**2**	**5**
D5	Inappropriate Transfer to a Different Procedure	6	**10**			9	**2**	**2**	9	**8**	4	**10**	7	**5**	7	**1.2**	**1.2**	8	**5**	**5**	14	**2.5**	19	**2**			5	**2**	**5**
D6	Decision to Delay Action	6	**10**			9	**2**	**2**	9	**8**	4	**10**	7	**5**	7	**1.2**	**1.2**	8	**5**	**5**	14	**2.5**	19	**2**			5	**2**	**5**
D7	Inappropriate Strategy Chosen	6	**10**			9	**2**	**2**	9	**8**	4	**10**	7	**5**	7	**1.2**	**1.2**	8	**5**	**5**	14	**2.5**	19	**2**			5	**2**	**5**
A1	Incorrect Timing	6	**10**			9	**5**		9	**8**	4	**3**	7	**5**	7	**1.2**		8	**2**		14	**2.5**	19	**2**			5	**5**	
A2	Incorrect Operation of Component/Object	6	**10**			9	**5**		9	**8**	4	**3**	7	**5**	7	**1.2**		8	**2**		14	**2.5**	19	**2**			5	**5**	
A3	Action on Wrong Component / object	6	**10**			9	**5**		9	**8**	4	**3**	7	**5**	7	**1.2**		8	**2**		14	**2.5**	19	**2**			5	**5**	

Table 14-10: Summary of data gathered for estimating parameter r_j (PIFs 7-9)

CFMs and ID		STRESS							TASK LOAD								TIME CONSTRAINT					
		NARA		SPAR-H			CREAM		NARA		SPAR-H				CREAM		SPAR-H		CREAM			
ID	CFMs	ID	Xplier	ID	Xplier	Xplier	ID	Xplier	ID	Xplier	ID	Xplier	ID	Xplier	ID	Xplier	ID	Xplier	ID		Xplier	Xplier
I1	Key Alarm not Responded to (intentional & unintentional)	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
I2	Data Not Obtained (Intentional)	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
I3	Data Discounted	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
I4	Decision to Stop Gathering Data	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
I5	Data Incorrectly Processed	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
I6	Reading Error	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
I7	Information Miscommunicated	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
I8	Wrong Data Source Attended to	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
I9	Data Not Checked with Appropriate Frequency	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
D1	Plant/System State Misdiagnosed	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
D2	Procedure Misinterpreted	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
D3	Failure to adapt procedures to the situation	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
D4	Procedure Step Omitted (Intentional)	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
D5	Inappropriate Transfer to a Different Procedure	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
D6	Decision to Delay Action	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
D7	Inappropriate Strategy Chosen	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	**5**
A1	Incorrect Timing	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	
A2	Incorrect Operation of Component/Object	18	**2**	2	**2**	**5**			1	**24**	3	**2**	3	**5**			1	**10**	6		**5**	
A3	Action on Wrong Component / object	18	**2**	2	**2**	**5**			1	**24**		**2**	3	**5**			1	**10**	6		**5**	

14.4.6.3 Data and sources used in estimating parameter r_j

Parameter r_j, the multiplier is a number used to indicate the individual influence of a PIF on a CFM. The multiplier "1" implies that the PIF has no influence on the CFM i.e. it doesn't change the conditional probability of the CFM. Any number greater than 1 implies that the PIF has an influence on the CFM and the larger the number, the greater the influence. Note that r_j is used to relate l_i to q_{ij} i.e. $q_{ij} = r_j * l_i$. The data gathered and used in estimating r_j is indicated in Table 14-8 to Table 14-10.

14.5 General Method for Aggregation of Estimates from Various Sources

After gathering the data from the aforementioned sources, we obtained a variety of estimates for each data point in our model as shown in the previous sections. The next step was to aggregate these estimates into a single representative estimate for each of these data points. Hence the focus on this section is to discuss a formal and structured aggregation method.

Bayesian methods seem to be favored by many researchers in the field. Among the Bayesian methods proposed are those by [109] and [110]. Even though the underlying philosophy of these methods is the same, the specific structures are highly dependent on the assumptions regarding handling such issues as dependence and calibration. These methods also vary depending on the type of data to which they apply. The quantity of interest may be a fixed unknown value (such as the length of a table) or an inherently variable quantity (such as the age of children in a certain school). The data obtained may come in many ways, including: a point estimate, parameters of a distribution and upper/lower bounds. The challenge for the decision maker is to figure out a way to correctly take full advantage of the data provided. We will present the

Bayesian methods for aggregation data from different sources assuming that the users of their estimates know the nature of the unknown quantity (i.e. if it is a single-value or distributed).

The Bayesian formulation is simple conceptually. Each data source is simply treated as a piece of evidence on the unknown of interest (UOI). The estimate is then used to update the analyst's own (prior) estimate through Bayes' theorem. We will discuss the basic techniques for a number of important classes of problems.

14.5.1 Single Data Source Methods

This covers cases where a single data source provides an estimate x* for an unknown quantity x. The estimate is the evidence that can be used by the analyst to update his/or her state of knowledge about x, through Bayes theorem:

$$\pi_1(x \mid x^*) = \frac{L(x^* \mid x)\pi_0(x)}{\int_{\forall x} L(x^* \mid x')\pi_0(x')dx'} \qquad (14\text{-}7)$$

where $\pi_0(x)$ is the prior distribution representing the state of knowledge about the unknown quantity x, x* is the data source's estimate of the value of x, L(x* | x) is the likelihood of the evidence given that the true value of the unknown quantity is x, and p1(x | x*) is the posterior distribution representing the updated state of knowledge about the unknown quantity.

The problem is thus reduced to the assessment of π_0 and L by the analysts. The key element in this approach is the likelihood. The data source estimates that the true value of x is between x* and x* + dx* is L(x* | x)dx*. In fact, the likelihood function is a measure of the accuracy of the data source's estimate in the analyst's eye. The shape and functional form of the likelihood may differ from one data source to another for the same unknown quantity. We also note that the form of the likelihood function, in general, is different for the assessments of different quantities obtained from the same data source. Further, the analysts can either weaken or strengthen the weight of the each data source's estimate through specification of L.

14.5.1.1 Additive Error Method

In this method, the analyst treats the data source's estimate (variable X*) as the sum of two terms:

$$X^* = x + \varepsilon \quad \text{(14-8)}$$

where x is the true value and ε an error term (itself a random variable).

The mean of the estimate obtained from the data source in this case is $\overline{X}^* = x + \overline{\varepsilon}$. This means that the analyst expects the estimate to be biased by an amount $\overline{\varepsilon}$. Under the further assumption that the error is symmetrically distributed about its mean $\overline{\varepsilon}$, a reasonable parametric distribution of ε is the normal distribution. The normal error model emerges if one assumes that many factors with uncertain magnitudes contribute to the data sources' error, and that the error is the sum of the effects of such factors.

With the assumption of normality for ε, the distribution of X* given x is also normal. Therefore, the likelihood function of the additive error model is given by:

$$L(x^*|x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left[\frac{x^* - (x+\overline{\varepsilon})}{\sigma}\right]^2} \quad \text{(14-9)}$$

where σ is the standard deviation of the (normal) error distribution.

14.5.1.2 Multiplicative Error Method

This covers the case where the data source’s estimate is viewed as the product of the true value and a random error ε:

$$X^* = x\varepsilon \tag{14-10}$$

Taking logarithm of this relation gives:

$$\ln(X^*) = \ln(x) + \ln(\varepsilon) \tag{14-11}$$

If we further assume that $\ln(\varepsilon)$ is normally distributed, the likelihood function of X^* given x is a lognormal distribution:

$$L(x^*|x) = \frac{1}{\sqrt{2\pi}\sigma x^*} e^{-\frac{1}{2}\left[\frac{\ln x^* - (\ln x + \ln b)}{\sigma}\right]^2} \tag{14-12}$$

where b (a multiplicative bias term) is the median of ε (ε_{50}).

If we now choose a lognormal prior distribution based on some experimental evidence by [111], [112] that suggest that lognormal assumption is realistic:

$$\pi_0(x) = \frac{1}{\sqrt{2\pi}\sigma_0 x} e^{-\frac{1}{2}\left[\frac{\ln x - \ln x_0}{\sigma_0}\right]^2} \tag{14-13}$$

Since the lognormal prior and lognormal likelihood are conjugate pairs, the posterior distribution will also be lognormal:

$$\pi_1(x|x_1^*) = \frac{1}{\sqrt{2\pi}\sigma_p x} e^{-\frac{1}{2}\left[\frac{\ln x - \mu}{\sigma_p}\right]^2} \tag{14-14}$$

where $\mu = \omega0\ln(x0) + \omega[\ln(x^*)-\ln(b)]$, and σ_p, ω_0, and ω are defined as in the additive error case.

The median of the posterior distribution is:

$$x_{50} = e^{\mu} = \left(\frac{x^*}{b}\right)^{\omega} x_0^{\omega_0} \quad (14\text{-}15)$$

The posterior median is the weighted geometric mean of the analyst's prior median estimate (x_0), and the estimate obtained from the data source, is adjusted by dividing it by the bias factor.

14.5.2 Distributed Quantities

This section covers the case where the quantity of interest has an underlying variability, and the estimates from different data sources come in the form of estimates of possible values of that quantity [113]. This situation arises when the provided estimates are based on sub-populations of a non-homogeneous population. The variability in the numerical estimates reflects not only the uncertainty in each data source's way of obtaining the individual estimates, but also the inherent difference between the sub-populations being considered by the data sources. It is assumed that estimates from the data sources is a set of values given by:

$$E = \{x^*_1, x^*_2, \dots, x^*_N\} \quad (14\text{-}16)$$

where x^*_i is the estimate from the i^{th} data source for an unknown quantity x, with the recognition that the particular value being estimated by that data source may be different from that being estimated by another.

The objective is to develop an estimate of the distribution representing the variability of x given the evidence presented by $E = \{x^*_1, x^*_2, \dots, x^*_N\}$. As before, from a conceptual Bayesian point of view, use of an estimate from a data source involves updating belief concerning an unknown, u, in light of the set of estimates from different sources:

$$\pi_1(u \mid E) = \frac{L(E \mid u)\pi_0(u)}{\int\limits_{\forall u} L(E \mid u')\pi_0(u')du'} \qquad \text{(14-17)}$$

where u is the unknown of interest (UOI), E is the set of estimates about the value of u (the analyst treats this set of estimates as evidence/data), $\pi_0(u)$ is the analyst's prior state-of-knowledge on u, $\pi_1(u \mid E)$ is the analyst's posterior state-of-knowledge on u after receiving the evidence, and $L(E \mid u)$ is the likelihood of observing the evidence E given that the true value of the unknown quantity is u.

In the case of interest the unknown is indeed a probability distribution denoted f(x) representing the range of values of x that were the subject of estimation by the different sources. In this sense, f(x) can be called 'source-to-source variability' distribution of x. To proceed, we simplify the problem by postulating that the unknown distribution is a member of a parametric family of distributions, and write it as $f(x \mid \boldsymbol{\theta})$. We then need to estimate the set of parameters $\boldsymbol{\theta} = \{\boldsymbol{\theta}_1, \boldsymbol{\theta}_2, ..., \boldsymbol{\theta}_m\}$ using Bayes theorem:

$$\pi_1(\boldsymbol{\theta} \mid E) = \frac{L(E \mid \boldsymbol{\theta})\pi_0(\boldsymbol{\theta})}{\int\limits_{\forall \boldsymbol{\theta}} L(E' \mid \boldsymbol{\theta}')\pi_0(\boldsymbol{\theta}')d\boldsymbol{\theta}'} \qquad \text{(14-18)}$$

The likelihood function, $L(E \mid \boldsymbol{\theta})$, is the probability density that the set of estimates is $E = \{x^*_1, x^*_2, \ldots, x^*_N\}$ given that the actual distribution of the quantity of interest (x) is a parametric distribution $f(x \mid \boldsymbol{\theta})$ with parameters $\boldsymbol{\theta}_1$ through to $\boldsymbol{\theta}_m$. Furthermore, we assume that the estimates are independent. Under the present set of conditions, we have:

$$L\left(x*_1, x*_2, \ldots, x*_N \mid \theta\right) = \prod_{i=1}^{N} L_i\left(x*_i \middle| \theta\right) \qquad \text{(14-19)}$$

where $L_i(x^*i \mid \boldsymbol{\theta})$ is the probability density that the ith source estimate is x^*_i when the set of parameters of the unknown distribution is **θ**. Note that the ith source estimate is a piece of information about the random variable x. More specifically, we are considering the case where x^*_i is an estimate of x_i which is one of the possible values of x. That is, each source is concerned with estimating x_i rather than the entire distribution of all x_i's.

Suppose that the decision maker knows the value of x_i. Then the accuracy of the each source's estimate as viewed by the analyst can be represented by a probability distribution g_i.

$$g_i = g_i(x^*_i \mid x_i) \qquad \text{(14-20)}$$

The distribution g_i is the analyst's probability density that the source's estimate is x^*_i when the source is attempting to estimate x_i. The fact is that the analyst does not know the value of x_i. What is known is that x_i is one of the possible value of x, and x is distributed according to $f(x \mid \boldsymbol{\theta})$. All possible values of x can be covered by integrating g_i over x:

$$L\left(x_i \mid \theta\right) = \int_{\forall x} g_i\left(x*_i \middle| x\right) f\left(x \middle| \theta\right) dx \qquad \text{(14-21)}$$

The result is the likelihood that the ith source's estimate is x^*_i when the set of the parameters of source-to-source variability distribution is **θ**.

For N independent sources we have:

$$\pi_1(\boldsymbol{\theta} \mid x^*_1, x^*_2, ..., x^*_N) = \frac{\left[\prod_{i=1}^{N} \int_{\forall x} g_i(x^*_i|x) f(x|\boldsymbol{\theta}) dx\right] \pi_0(\boldsymbol{\theta})}{\int_{\forall \boldsymbol{\theta}} \left[\prod_{i=1}^{N} \int_{\forall x} g_i(x^*_i|x) f(x|\boldsymbol{\theta}') dx\right] \pi_0(\boldsymbol{\theta}') d\boldsymbol{\theta}'} \quad (14\text{-}22)$$

This is the result of using Equations (14-21) in (14-19) to obtain the likelihood for all N sources which is then used in Bayes theorem in Equation (14-18).

The posterior distribution, $\pi_1(\boldsymbol{\theta} \mid x^*_1, x^*_2, ..., x^*_N)$, is a probability distribution over a family of distributions. It is a measure of the analyst's uncertainty about which member of the assumed family $f(x \mid \boldsymbol{\theta})$ is in fact the true distribution of x. Each value of the set $\boldsymbol{\theta}$, represents as a candidate with probability $\pi_1(\boldsymbol{\theta} \mid x^*_1, x^*_2, ..., x^*_N)d\boldsymbol{\theta}$. The most probable distribution is the one whose set of parameters, $\hat{\boldsymbol{\theta}}$, maximizes π_1. Such a set is the solution of the following system of simultaneous equations:

$$\left.\frac{\partial}{\partial \theta_j} \pi_1(\boldsymbol{\theta} \mid x^*_1, x^*_2, ..., x^*_N)\right|_{\theta_j = \hat{\theta}_j} = 0 \quad (14\text{-}23)$$

The method presented in this section has been used extensively, particularly in nuclear power risk studies for the development of component failure rate estimates from various sources including experts and generic data compilation. In all such applications, the data sources are assumed to be independent since the computational demands for handling dependence were considered excessive.

We will be applying the method of distributed quantities to show how to obtain a representative estimate for each parameter in our model. This method is chosen in order to capture the underlying source-to-source variability in the estimation of each parameter.

As an example, we used the Bayesian method of distributed quantities to demonstrate the estimation of parameter $\boldsymbol{q_{I61}}$ i.e. CFM I6 given PIF 1, using data mapped directly from the data sources (3 data points: 1.00E-03, 6.00E-03, 1.00E-02) as evidence. For this, we used R-DAT software [114] to perform the calculation leading to development of the "expected distribution" based on equation 14-22. We used the lognormal distribution to specify the source to source variability of $\boldsymbol{q_{I61}}$ estimates since it can be generally used to express orders of magnitude variations in the estimates of the quantity of interest. Figure 14-1 shows the cumulative distribution of $\boldsymbol{q_{I61}}$ and the uncertainty bounds. Figure 14-2 shows the expected variability distribution of $\boldsymbol{q_{I61}}$ with median of 5.11E-03 and 90% bounds of 1.03E-03 and 1.01E-02.

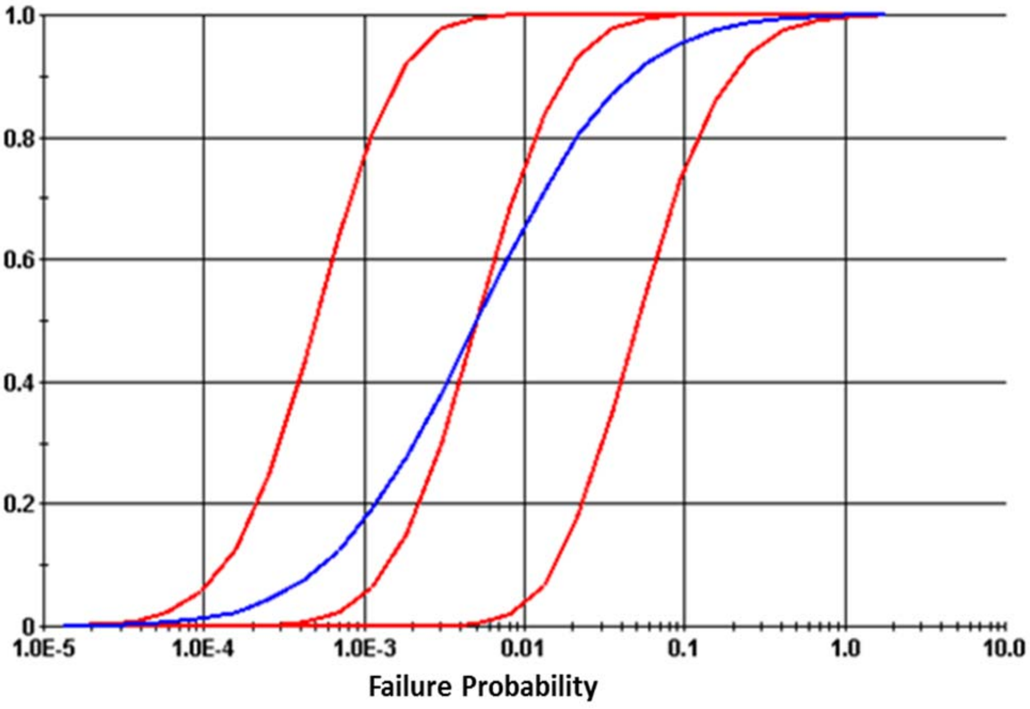


Figure 14-1: Cumulative Distribution of q_{I61} and Uncertainty Bounds

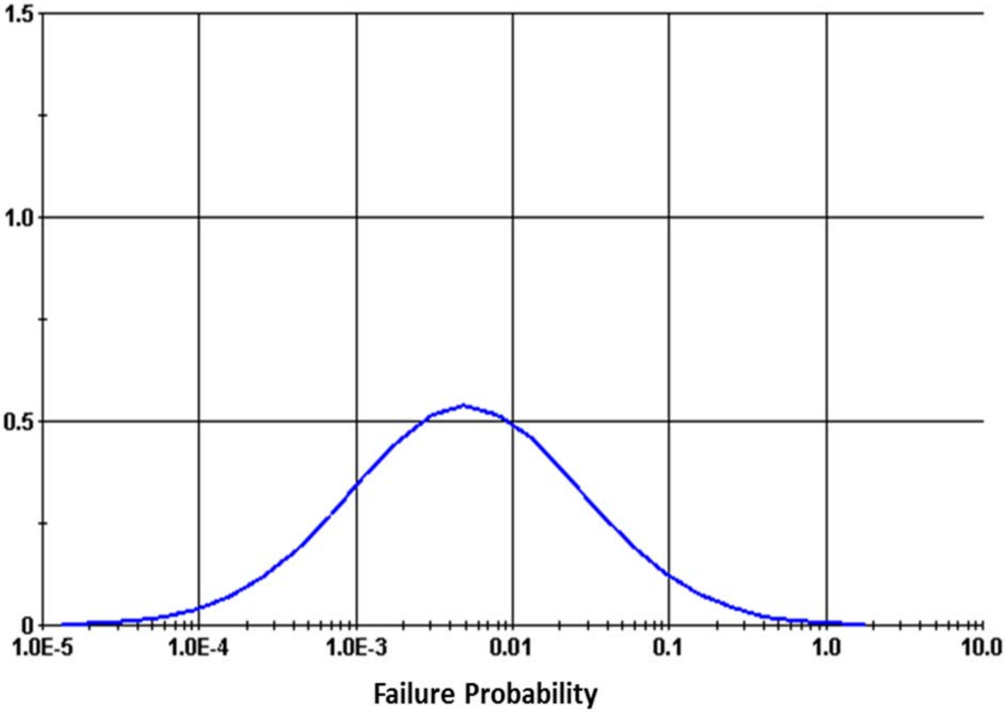


Figure 14-2: Expected Variability Distribution of q_{I61} and Uncertainty Bounds

Using this method, the median value obtained for each model parameter can be reasonably approximated using the geometric mean [115]. For the same parameter, we obtained an estimate of 4.00E-03 using the geometric mean. Hence, we used the geometric mean to estimate the approximate median values of the other model parameters.

The geometric mean is a type of average which is used to estimate the typical value of a set of numbers by using the product of their values. It is generally defined as the nth root of the product of a set of numbers where n is the count of the numbers in the set. For a data set $\{y_1, y_2, \ldots, y_n\}$, its geometric mean is given by:

$$\left(\prod_{i=1}^{n} y_i\right)^{1/n} = \sqrt[n]{y_1\, y_2, \dots, y_n} \tag{14-24}$$

Applying Equation (14-24), we were able to provide a single representative estimate for the respective model parameters. Table 14-11 shows each CFM and the estimated leak factor $\boldsymbol{l_i}$. Table 14-12 shows the multiplier $\boldsymbol{r_j}$ relating each CFM_i and PIF_j while

Table 14-13 shows parameter $\boldsymbol{q_{ij}}$, the conditional probability that a crew failure has occurred (CFM_i) given that a particular PIF_j is in the degraded state.

Table 14-11: CFMs and corresponding estimated leak factor l_i

ID	CFMs	Leak factors (l_i)
I1	Key Alarm not Responded to (intentional & unintentional)	1.28E-04
I2	Data Not Obtained (Intentional)	7.00E-02
I3	Data Discounted	7.00E-02
I4	Decision to Stop Gathering Data	2.65E-02
I5	Data Incorrectly Processed	8.37E-03
I6	Reading Error	8.46E-04
I7	Information Miscommunicated	6.00E-03
I8	Wrong Data Source Attended to	1.00E-03
I9	Data Not Checked with Appropriate Frequency	2.00E-02
D1	Plant/System State Misdiagnosed	4.31E-02
D2	Procedure Misinterpreted	2.45E-03
D3	Failure to adapt procedures to the situation	1.41E-02
D4	Procedure Step Omitted (Intentional)	1.00E-02
D5	Deviation from Procedure	1.00E-02
D6	Decision to Delay Action	1.00E-02
D7	Inappropriate Strategy Chosen	1.00E-02
A1	Incorrect Timing	1.49E-03
A2	Incorrect Operation of Component/Object	3.31E-03
A3	Action on Wrong Component / object	4.47E-04

Note that in order to populate the CPT for each CFM$_i$, we need parameters q_{ij} and l_i. Also, since $r_j * l_i = q_{ij}$, we used this to estimate q_{ij}. Thereafter, we combined the results with those mapped directly from the data sources (Table 14-13) to produce the final q_{ij} (Table 14-14), used to directly populate the CPT for each CFM$_i$ in our BBN model.

Table 14-12: CFMs and corresponding PIF multipliers r_j

		PIF ID and multiplier (r_j) for each CFM$_i$								
ID	**CFMs**	1	2	3	4	5	6	7	8	9
I1	Key Alarm not Responded to (intentional & unintentional)	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
I2	Data Not Obtained (Intentional)	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
I3	Data Discounted	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
I4	Decision to Stop Gathering Data	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
I5	Data Incorrectly Processed	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
I6	Reading Error	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
I7	Information Miscommunicated	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
I8	Wrong Data Source Attended to	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
I9	Data Not Checked with Appropriate Frequency	6.3	4.8	3.2	3.4	2.9	2.1	2.7	6.2	6.3
D1	Plant/System State Misdiagnosed	4.8	5.5	2.5	3.4	3.9	2.7	2.7	6.2	6.3
D2	Procedure Misinterpreted	4.8	5.5	2.5	3.4	3.9	2.7	2.7	6.2	6.3
D3	Failure to adapt procedures to the situation	4.8	5.5	2.5	3.4	3.9	2.7	2.7	6.2	6.3
D4	Procedure Step Omitted (Intentional)	4.8	5.5	2.5	3.4	3.9	2.7	2.7	6.2	6.3
D5	Deviation from Procedure	4.8	5.5	2.5	3.4	3.9	2.7	2.7	6.2	6.3
D6	Decision to Delay Action	4.8	5.5	2.5	3.4	3.9	2.7	2.7	6.2	6.3
D7	Inappropriate Strategy Chosen	4.8	5.5	2.5	3.4	3.9	2.7	2.7	6.2	6.3
A1	Incorrect Timing	9	6.3	4	7.1	3.1	2.9	2.7	6.2	7.07
A2	Incorrect Operation of Component/Object	9	6.3	4	7.1	3.1	2.9	2.7	6.2	7.07
A3	Action on Wrong Component / object	9	6.3	4	7.1	3.1	2.9	2.7	6.2	7.07

Table 14-13: Conditional probability of CFM given a PIF (I - 9) in a degraded state (q_{ij})

ID	CFMs	PIFs								
		1	2	3	4	5	6	7	8	9
I1	Key Alarm not Responded to (intentional & unintentional)									
I2	Data Not Obtained (Intentional)									
I3	Data Discounted									
I4	Decision to Stop Gathering Data									
I5	Data Incorrectly Processed	1.00E-02								
I6	Reading Error	4.00E-03	3.00E-03					8.00E-03		
I7	Information Miscommunicated									
I8	Wrong Data Source Attended to									
I9	Data Not Checked with Appropriate Frequency									
D1	Plant/System State Misdiagnosed					7.00E-02		6.80E-02		
D2	Procedure Misinterpreted		2.90E-02							
D3	Failure to adapt procedures to the situation									
D4	Procedure Step Omitted (Intentional)									
D5	Deviation from Procedure									
D6	Decision to Delay Action									
D7	Inappropriate Strategy Chosen	1.30E-03				3.44E-02				
A1	Incorrect Timing							1.50E-02		3.50E-03
A2	Incorrect Operation of	7.00E-04				2.10E-02		4.20E-02	1.30E-03	
A3	Action on Wrong Component / object	2.00E-03					7.80E-04			

Table 14-14: Final q_{ij} used in populating the CPT for each CFM$_i$

ID	CFMs	PIFs								
		HSI	Procedures	Resources	Team Effectiveness	Knowledge / Abilities	Bias	Stress	Task load	Time constraint
I1	Key Alarm not Responded to (intentional & unintentional)	8.03E-04	6.18E-04	4.08E-04	4.39E-04	3.72E-04	2.72E-04	3.49E-04	7.98E-04	8.09E-04
I2	Data Not Obtained (Intentional)	4.38E-01	3.37E-01	2.22E-01	2.39E-01	2.03E-01	1.48E-01	1.90E-01	4.35E-01	4.41E-01
I3	Data Discounted	4.38E-01	3.37E-01	2.22E-01	2.39E-01	2.03E-01	1.48E-01	1.90E-01	4.35E-01	4.41E-01
I4	Decision to Stop Gathering Data	1.66E-01	1.27E-01	8.40E-02	9.05E-02	7.67E-02	5.60E-02	7.18E-02	1.64E-01	1.67E-01
I5	Data Incorrectly Processed	2.29E-02	4.03E-02	2.66E-02	2.86E-02	2.43E-02	1.77E-02	2.27E-02	5.20E-02	5.28E-02
I6	Reading Error	4.60E-03	3.50E-03	2.69E-03	2.89E-03	2.45E-03	1.79E-03	4.29E-03	5.26E-03	5.33E-03
I7	Information Miscommunicated	3.75E-02	2.89E-02	1.90E-02	2.05E-02	1.74E-02	1.27E-02	1.63E-02	3.73E-02	3.78E-02
I8	Wrong Data Source Attended to	6.26E-03	4.81E-03	3.17E-03	3.42E-03	2.90E-03	2.11E-03	2.71E-03	6.21E-03	6.30E-03
I9	Data Not Checked with Appropriate Frequency	1.25E-01	9.63E-02	6.35E-02	6.84E-02	5.80E-02	4.23E-02	5.43E-02	1.24E-01	1.26E-01
D1	Plant/System State Misdiagnosed	2.06E-01	2.36E-01	1.09E-01	1.47E-01	1.09E-01	1.15E-01	8.92E-02	2.68E-01	2.71E-01
D2	Procedure Misinterpreted	1.17E-02	1.97E-02	6.17E-03	8.38E-03	9.62E-03	6.51E-03	6.65E-03	1.52E-02	1.54E-02
D3	Failure to adapt procedures to the situation	6.77E-02	7.76E-02	3.56E-02	4.84E-02	5.55E-02	3.76E-02	3.84E-02	8.79E-02	8.91E-02
D4	Procedure Step Omitted (Intentional)	4.78E-02	5.49E-02	2.52E-02	3.42E-02	3.93E-02	2.66E-02	2.71E-02	6.21E-02	6.30E-02
D5	Inappropriate Transfer to a Different procedure	4.78E-02	5.49E-02	2.52E-02	3.42E-02	3.93E-02	2.66E-02	2.71E-02	6.21E-02	6.30E-02
D6	Decision to Delay Action	4.78E-02	5.49E-02	2.52E-02	3.42E-02	3.93E-02	2.66E-02	2.71E-02	6.21E-02	6.30E-02
D7	Inappropriate Strategy Chosen	7.89E-03	5.49E-02	2.52E-02	3.42E-02	3.68E-02	2.66E-02	2.71E-02	6.21E-02	6.30E-02
A1	Incorrect Timing	1.35E-02	9.35E-03	5.97E-03	1.06E-02	4.64E-03	4.37E-03	7.80E-03	9.28E-03	1.06E-02
A2	Incorrect Operation of Component/Object	4.57E-03	2.07E-02	1.32E-02	2.34E-02	1.47E-02	9.68E-03	1.94E-02	5.17E-03	2.34E-02
A3	Action on Wrong Component / object	2.84E-03	2.80E-03	1.79E-03	3.16E-03	1.39E-03	1.01E-03	1.21E-03	2.78E-03	3.16E-03

14.6 SACADA Database as a future data source

The lack of sufficient and appropriate human performance data is one of the key factors affecting HEP estimation in particular, and the quality of HRA in general. In an attempt to address this issue, the US NRC is sponsoring the Scenario Authoring, Characterization, and Debriefing Application (SACADA) database project [30], [31]. This project which is a part of the US NRC's HRA data program [31], is an on-going data collection effort aimed at collecting human performance data / information for use in human reliability applications. The SACADA tool was developed so that it could be suitable for implementation in the operator training program of NPPs for collection of operator training / simulator exercise information. It is aimed at being a long term date collection program which identifies a set of anchor HEPs with sufficient contextual information for use as reference points in HEP estimation. It utilizes the macrocognitive functions of detecting / noticing, sense-making / understanding / diagnosis, deciding/response planning, executing actions, communicating / coordinating (team functions), and supervising /directing personnel [30]. These are the same functions on which our CFM-PIF framework is built.

Each training scenario starts with a plant initial condition which is followed by a set of plant malfunctions. For each malfunction, a set of important operator task are pre-identified. Each task is represented by a training objective element (TOE), which is the basic data unit (data point). Each TOE consists of context (in terms of situational factors that affect success in a TOE) and performance results (in terms of error modes, causes, recovery) information.

According to [30], it is estimated that about 2800 TOEs will be produced per reactor per year. Therefore, when collected from a number of reactor units, the data produced should be sufficient to support HRA.

Relating the SACADA database to our HRA methodology, the human performance results consist of error modes which map to our CFMs, Table 7-3, and error causes which map to our PIFs, Table A3. When obtained, this information would be incorporated into our model parameter estimation process (as another data source) using the Bayesian model uncertainty treatment method (method of distributed quantities) discussed earlier in this chapter. The context results will aid in enriching the narratives for each scenario of the particular HFE in our qualitative analysis. Hence, our interest in using the SACADA database to provide the needed statistical basis to support our methodology.

The results from the database can be recorded in tabular form as shown in Table 14-15. For each TOE, the CFMs that occur and the relevant PIFs can be recorded. Note that the PIFs are set at the beginning of the scenario by the trainer. These results can also be represented in form of a BBN as shown in Figure 14-3. From this, we would learn the structure and obtain relevant information required to quantify our BBN i.e. reduce the structure to that of our BBN.

Table 14-15: A sample tabular representation of the future SACADA output

TOE	Output (Results)												
	Human Performance Results												Context
	CFMs							PIFs					
	I1	I2	...	D7	A1	A2	A3	1	2	3	....	9	
1	x					x		x	x			x	x
2		x		x			x			x	x		x
3	x		x		x			x				x	x
4			x			x	x	x	x				x
5	x				x				x	x		x	x
6		x			x		x	x			x		x
:	x			x					x		x		x
:		x				x		x				x	x
10000		x				x					x		x

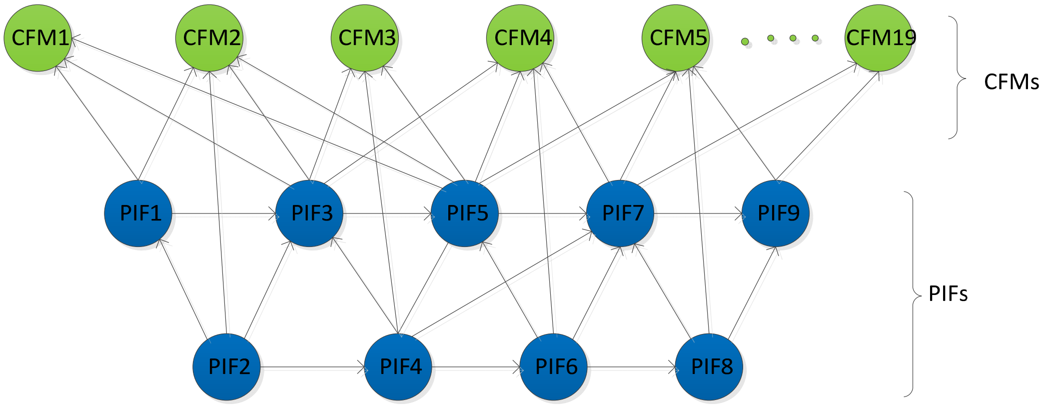


Figure 14-3: A Sample BBN representation of the future SACADA database output

14.7 Quantitative Results for Model Parameters

Due to the application of the Leaky NoisyOR function, the CPT for each CFM in our BBN model has two rows and ten columns. The first row contains the 9 $\boldsymbol{q_{ij}}$s i.e. $P(CFM_i = \text{failure} \mid PIF_j = \text{degraded}, PIF_k = \text{nominal for each } k \neq j)$ and a leak factor $\boldsymbol{l_i}$ associated with each CFM_i. The second row is the complement of each data point in the column above it i.e. $1 - \boldsymbol{q_{ij}}$ and $1- \boldsymbol{l_i}$. Therefore, each CFM row in Table 14-14 contains the data points for the first row of its CPT and the complement of each of these data points provides the data points for the second row.

Using these data points, we developed the CPTs required for all the CFMs in our Model. Thereafter, we created our BBN model using GeNie BBN software [90] with the CFM nodes being noisy-max nodes and populated the CPTs with the respective data points. For the PIF nodes, we inputted different combinations of marginal probabilities and ran the model to obtain the joint conditional probability of each CFM_i given the PIFs i.e. $P(CFM_i \cap PIF_1, PIF_2, \ldots, PIF_9)$. See Table 14-16.

Table 14-16: Joint Conditional probability of CFMs given different PIF levels

ID	CFMs	PIF states and levels		
		Degraded (D = 1, N = 0)	Mid way (D = 0.5, N = 0.5)	Nominal (D =0, N = 1)
I1	Key Alarm not Responded to (intentional & unintentional)	4.00E-02	2.10E-02	1.00E-04
I2	Data Not Obtained (Intentional)	9.69E-01	7.92E-01	7.00E-02
I3	Data Discounted	9.69E-01	7.92E-01	7.00E-02
I4	Decision to Stop Gathering Data	6.77E-01	4.28E-01	2.60E-02
I5	Data Incorrectly Processed	3.11E-01	1.72E-01	9.00E-03
I6	Reading Error	4.20E-02	2.20E-02	1.00E-03
I7	Information Miscommunicated	2.16E-01	1.16E-01	6.00E-03
I8	Wrong Data Source Attended to	3.90E-02	2.00E-02	1.00E-03
I9	Data Not Checked with Appropriate Frequency	5.68E-01	3.42E-01	2.00E-02
D1	Plant/System State Misdiagnosed	8.51E-01	6.00E-01	4.30E-02
D2	Procedure Misinterpreted	1.00E-01	5.20E-02	2.00E-03
D3	Failure to adapt procedures to the situation	4.83E-01	2.82E-01	1.60E-02
D4	Procedure Step Omitted (Intentional)	3.36E-01	1.87E-01	1.00E-02
D5	Inappropriate Transfer to a Different procedure	3.36E-01	1.87E-01	1.00E-02
D6	Decision to Delay Action	3.36E-01	1.87E-01	1.00E-02
D7	Inappropriate Strategy Chosen	3.07E-01	1.70E-01	1.00E-02
A1	Incorrect Timing	6.90E-02	3.60E-02	1.00E-03
A2	Incorrect Operation of Component/Object	1.24E-01	6.50E-02	3.00E-03
A3	Action on Wrong Component / object	2.20E-02	1.10E-02	4.00E-04

Note that each PIF has two states which equate to either the degraded state (D) or the nominal state (N). From Table 14-16, we observe that:

- The estimates obtained are consistent with the expected trend i.e. when all the PIFs are set to the degraded state (marginal probability of the degraded state = 1, marginal probability of the nominal state = 0), each PIF has the most negative influence on crew performance by degrading it. The joint conditional probability of each CFM_i is at its highest.
- When all the PIFs are set to the nominal state (marginal probability of the degraded state = 0, marginal probability of the nominal state = 1), the joint conditional probability of each CFM_i is at its lowest.
- When all the PIFs are set to the nominal state, the joint conditional probability of each CFM is approximately equal to the leak factor, $\boldsymbol{l_i}$ $P(CFM_i = \text{failure} \mid PIF_1 = \text{nominal} ,..., PIF_9 = \text{nominal})$. This verifies the claim that $\boldsymbol{l_i}$ is the probability that a crew failure has occurred even when there is no influence from any of the PIFs.

Using the above estimates (Table 14-16) which serve as inputs to our human response model (IDA), we obtained estimates of the conditional probabilities of each phase of the IDA model and the HFE (Table 14-17). This was done using IRIS software [84].

Table 14-17: HEP Estimates for each phase of our IDA model and overall HFE

IDA model	PIF states and levels		
	Degraded (D = 1, N = 0)	Mid way (D = 0.5, N = 0.5)	Nominal (D =0, N = 1)
HFE	1.00E+00	9.99E-01	2.71E-01
Information processing phase (I)	1.00E+00	9.89E-01	1.88E-01
Decision making phase (D)	9.86E-01	8.79E-01	9.72E-02
Action phase (A)	2.02E-01	1.09E-01	4.45E-03

The conditional HEP estimates from Table 14-17 are consistent with the expected trend. The conditional probability of each IDA phase and HFE is highest when all the PIFs are set to the degraded state and lowest when they are all set to the nominal state. Also, the conditional probabilities of the action errors in all levels of the PIFs are consistently lower than those of the decision making errors.

However, these estimates are generally higher than expected when all PIFs are in the nominal state and midway PIF levels i.e. when the HRA analyst is not sure if the PIFs are all in the nominal or degraded state respectively. Hence, there is a need to calibrate the data input to the model.

14.8 Data Calibration

The ideal situation would be to have a source that can provide the needed data input required to estimate our model parameters. Since that was not possible, we had to obtain data from different sources. Each source makes some assumptions (which may be different from ours) when using their data in estimating HEPs. Also, some of the sources (NARA, SPAR-H) have some form of *normalization factor* incorporated into the formulation used in their HEP estimation process. Therefore, we decided to calibrate the resulting data before inputting it in our model.

We chose to use SPAR-H nominal HEP values to aid in our data calibration process. This is because SPAR-H is one of the most widely used methods in NPP HRA. Also, it has nominal HEP values associated with diagnosis tasks (1.00E-02) and action tasks (1.00E-03) in general. The nominal HEP for diagnosis tasks could be interpreted as the resulting HEP obtained from all the CFMs in both the I and D phases of our model. Also, the nominal HEP for action tasks could be interpreted as the resulting HEP obtained from all the CFMs in the A phase. Since the leak factor $\boldsymbol{l_i}$ represents the conditional probability that a crew failure has occurred even when there is no influence from any of the PIFs i.e. P(CFM$_i$ = failure | PIF$_1$ = nominal ,..., PIF$_9$ = nominal), we decided to use the nominal HEPs from SPAR-H to calibrate this parameter in our model.

14.8.1 Calibration of $\boldsymbol{l_{I1}}$ to $\boldsymbol{l_{D7}}$

To calibrate the leak factor $\boldsymbol{l_i}$ for all the 16 CFMs in both the I and D phase ($\boldsymbol{l_{I1}}$ to $\boldsymbol{l_{D7}}$), we normalized the estimated nominal HEP (for both the I and D phase) to that of SPAR-H (1.00E-02). This was done using the following formulation:

$$\boldsymbol{l_i}^* = \frac{10^{-2}}{0.30249}\boldsymbol{l_i} \qquad (14\text{-}25)$$

Where $\boldsymbol{l_i}$ represents the leak factor for each CFM$_i$ in I and D phase (Table 14-11), $\boldsymbol{l_i}$***** represents the calibrated leak factors. Note that:

$$\sum_{i=1}^{16} \boldsymbol{l_i} = 0.30249 \qquad (14\text{-}26)$$

And

$$\sum_{i=1}^{16} \boldsymbol{l_i}^* = 10^{-2} \quad (14\text{-}27)$$

14.8.2 Calibration of l_{A1} to l_{A3}

The calibration of the leak factor l_i for the 3 CFMs in both the A phase (l_{A1} to l_{A3}) was done by normalizing the estimated nominal HEP (for the A phase) to that of SPAR-H (1.00E-03), using the following formulation:

$$\boldsymbol{l_i}^* = \frac{10^{-3}}{0.00525}\, \boldsymbol{l_i} \quad (14\text{-}28)$$

Where l_i represents the leak factor for each CFM$_i$ in A phase (Table 14-11), l_i***** represents the calibrated leak factors. Also,

$$\sum_{i=1}^{3} \boldsymbol{l_i} = 0.00525 \quad (14\text{-}29)$$

And

$$\sum_{i=1}^{3} \boldsymbol{l_i}^* = 10^{-3} \quad (14\text{-}30)$$

14.8.3 BBN Model Output with Calibrated Inputs

Using the results obtained from the above calibration, we developed the updated CPTs for the CFMs. We inputted it into the BBN model with different combinations of marginal probabilities of PIFs and ran the model to obtain the joint conditional probability of each CFM$_i$ given the PIFs i.e. P(CFM$_i$ ∩ PIF$_1$, PIF$_2$, …, PIF$_9$). Also included in Table 14-18 are the calibrated leak factor estimates l_i*****.

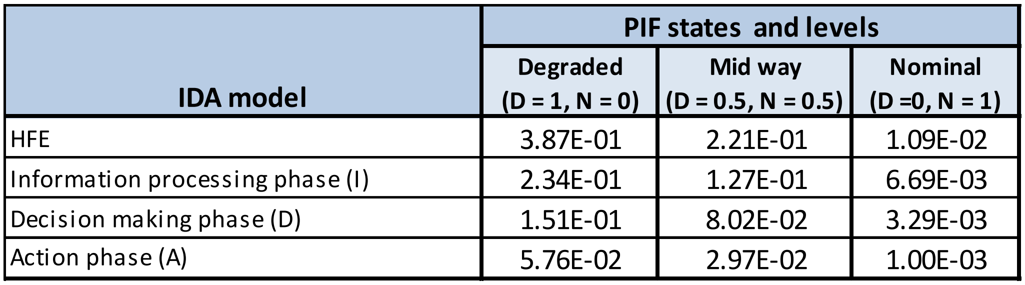
From Table 14-18, we observe that the estimates compare favorably to the GGTs in NARA and generic failure types in CREAM. They are consistent with the expected trends. The joint conditional probability of each CFM_i is at its highest when all the PIFs are set to the degraded state and lowest when all the PIFs are set to the nominal state. Also, the joint conditional probability of each CFM_i is approximately equal to the leak factor, $\boldsymbol{l_i}$ when all the PIFs are set to the nominal state.

Table 14-18: Joint Conditional Probabilities of CFMs given PIFs (calibrated)

ID	CFMs	PIF states and levels			Leak factor
		Degraded (D = 1, N = 0)	Mid way (D = 0.5, N = 0.5)	Nominal (D =0, N = 1)	
I1	Key Alarm not Responded to (intentional & unintentional)	1.65E-04	8.47E-05	4.24E-06	4.24E-06
I2	Data Not Obtained (Intentional)	8.66E-02	4.52E-02	2.31E-03	2.31E-03
I3	Data Discounted	8.66E-02	4.52E-02	2.31E-03	2.31E-03
I4	Decision to Stop Gathering Data	3.35E-02	1.73E-02	8.75E-04	8.75E-04
I5	Data Incorrectly Processed	1.31E-02	6.72E-03	2.77E-04	2.77E-04
I6	Reading Error	2.95E-03	1.49E-03	2.80E-05	2.80E-05
I7	Information Miscommunicated	7.69E-03	3.95E-03	1.98E-04	1.98E-04
I8	Wrong Data Source Attended to	1.29E-03	6.60E-04	3.31E-05	3.31E-05
I9	Data Not Checked with Appropriate Frequency	2.54E-02	1.31E-02	6.61E-04	6.61E-04
D1	Plant/System State Misdiagnosed	7.93E-02	4.10E-02	1.42E-03	1.42E-03
D2	Procedure Misinterpreted	6.29E-03	3.19E-03	8.10E-05	8.10E-05
D3	Failure to adapt procedures to the situation	1.81E-02	9.32E-03	4.68E-04	4.68E-04
D4	Procedure Step Omitted (Intentional)	1.28E-02	6.60E-03	3.31E-04	3.31E-04
D5	Inappropriate Transfer to a Different Procedure	1.28E-02	6.60E-03	3.31E-04	3.31E-04
D6	Decision to Delay Action	1.28E-02	6.60E-03	3.31E-04	3.31E-04
D7	Inappropriate Strategy Chosen	1.80E-02	9.20E-03	3.31E-04	3.31E-04
A1	Incorrect Timing	1.72E-02	8.77E-03	2.85E-04	2.85E-04
A2	Incorrect Operation of Component/Object	3.64E-02	1.87E-02	6.30E-04	6.30E-04
A3	Action on Wrong Component / object	4.86E-03	2.47E-03	8.52E-05	8.52E-05

Using these estimates as inputs to our human response model (IDA), we obtained estimates of the conditional probabilities of each phase of the IDA model and the HFE (Table 14-19). This was done using IRIS software [84].

Table 14-19: HEP Estimates with Calibrated Inputs



IDA model	PIF states and levels		
	Degraded (D = 1, N = 0)	Mid way (D = 0.5, N = 0.5)	Nominal (D =0, N = 1)
HFE	3.87E-01	2.21E-01	1.09E-02
Information processing phase (I)	2.34E-01	1.27E-01	6.69E-03
Decision making phase (D)	1.51E-01	8.02E-02	3.29E-03
Action phase (A)	5.76E-02	2.97E-02	1.00E-03

The estimates from Table 14-19 are still consistent with the expected trend. The conditional probability of each IDA phase and HFE is highest when all the PIFs are set to the degraded state and lowest when they are all set to the nominal state. As expected, the nominal HEP for the A phase errors is equal to 1.00E-3 and the sum of the nominal HEP for the I and D phase errors is equal to 1.00E-02. Also, the HEPs of the action errors in all levels of the PIFs are consistently lower than those of the decision making errors.

However, the conditional HEP estimates are generally lower than expected when all PIFs are set to the degraded state. In particular, we would expect the conditional HEP estimate for the HFE to be closer to 1. This would be the subject for future research after expert opinion and the data from SACDA database are incorporated into the model parameter estimation process.

15 Examples on Various Application of Methodology

In this chapter, we will be providing examples to demonstrate possible applications of our HRA methodology, including various important concepts developed as part of this research work. Since the specific instance of this methodology is applicable to NPPs, the examples presented are tailored towards applications like that of accident sequence precursor (ASP) analysis (portraying an event that actually happened and taking it hypothetically to the what-if scenarios), significant determination process (SDP) (events that involve performance deficiencies), event assessment (looking at an event and trying to understand its significance in terms of its causes and whether to take actions to prevent future occurrences e.g. changing regulations), power operations (when the reactor is operating normally and something goes wrong, requiring crew response), and shut down operations (when the reactor is transitioning to shut down or start-up and something goes wrong, requiring crew response).

We will be using an ASP analysis example to demonstrate our entire methodology i.e. both qualitative and quantitative analysis. Thereafter, other examples will focus on specific aspects of our qualitative analysis methodology like building CRTs, developing fault trees to link the CFMs to the respective branch points in the CRT, merging CRTs to form larger ones etc.

15.1 Accident Sequence Precursor (ASP) Analysis Example Application

We will be using the H. B. Robinson event “Electrical Fault Causes Fire and Subsequent Reactor Trip with a Loss of Reactor Coolant Pump Seal Injection and

Cooling” [116] as an example to demonstrate our entire methodology. Below is a brief description of the event and some key details according to the final precursor analysis report [116]:

- “At 18:52 on March 28, 2010, with the H. B. Robinson Steam Electric Plant, Unit No. 2, operating in Mode 1 at approximately 100% power, an electrical feeder cable failure to 4kV non-vital Bus 5 caused an arc flash and fire. Bus 5 failed to isolate from non-vital 4kV Bus 4 due to a failure of Breaker 52/24 to open, which resulted in reduced voltage to Reactor Coolant Pump (RCP) B and a subsequent reactor trip on Reactor Coolant System (RCS) loop low flow. Subsequent to the reactor trip, an automatic safety injection (SI) occurred due to RCS cool down. Plant response was complicated by equipment malfunctions and failure of the operating crew to understand plant symptoms and properly control the plant. During plant restoration the operating crew attempted to reset an electrical distribution system control relay prior to isolating the fault, which re-initiated the electrical fault and caused a second fire.”
- “The Unit Auxiliary Transformer (UAT) failed due to an overload condition caused by the ground fault on Bus 5. This caused a fast transfer of 4kV Buses 1, 4, and 5 to the Startup Transformer (SUT).”
- “The reactor automatically tripped as designed due to low reactor coolant flow caused by an under-voltage condition on Bus 4, which led to a decrease in RCP B speed. Main feedwater (MFW) was isolated when the SI signal occurred, as designed. Auxiliary feedwater (AFW) initiated as designed and provided makeup to the steam generators.”

- RCP seal injection to the RCPs was lost initially due to both running charging pumps being de-energized when the transient occurred. Operators restored seal injection by restarting two charging pumps (only one is required to adequately cool the seals) within one minute.
- RCP seal cooling [via Component Cooling Water (CCW)] was unavailable due to the closing of Flow Control Valve (FCV) 626 (thermal barrier outlet isolation flow control valve) which stopped flow from the thermal barrier heat exchangers. FCV-626 closed due to momentary loss of power to vital Bus E2 and flow control circuit being de-energized (via Instrument Bus 4) causing the closure of FCV-626 due to an inaccurate high-flow signal when the flow sensor lost power. Operators restored seal cooling in 39 minutes by re-opening FCV-626 (approximately 12 minutes after RCP seal injection became inadequate). This recovery was delayed because operators initially failed to use annunciator procedures that directed the opening of FCV-626.
- RCP seal injection was determined to be inadequate to fulfill its safety function from 19:19 until approximately 19:58 (~39 minutes).This was due to the opening of Chemical and Volume Control (CVC) Valve 310A (charging flow valve to Loop 1) because of a loss of instrument air; thus, diverting charging flow from the RCP seals to the RCS. The loss of instrument air occurred due to a Phase-A Containment Isolation (normal) function of SI actuation signal). The valve failed fully open 19 minutes after the SI signal. Operators were unaware that the opening of CVC-310A caused the diversion of RCP seal injection away from the RCP seals. The loss of seal injection flow instrumentation within the main control

room and an inadequate emergency operating procedure (EOP) step for determining seal injection flow contributed to operators failing to determine that seal injection was inadequate.

In summary, the success criterion for this event (loss of reactor coolant pump (RCP) seal injection and cooling) is to restore RCP seal cooling or seal injection within 13 minutes (after the loss of both cooling and injection) from the control room to avoid the occurrence of voiding within the RCPs. After 13 minutes, the temperature will be very high which could cause thermal shock and the entire seal could be lost based on studies performed by Westinghouse. In order to restore seal injection and cooling, the crew needs to either open FCV-626 to restore CCW to the RCP seals or close CVC valve 310A to restore charging flow to the RCP seals. According to the report, the crew re-opened FCV-626 exactly 12 minutes after RCP seal injection became inadequate.

15.1.1 Qualitative Analysis

We will conduct the qualitative analysis by applying the methodology steps.

15.1.1.1 Step 1: Develop/Identify PRA scenarios for analysis

This involves the building of the event tree (ET) or event sequence diagram (ESD) for the initiating event (IE), selection of the PRA scenario and gathering of the required context information.

The ET was built for a loss of MFW transient initiating event with complications. The PRA scenario selected is that of a loss of seal cooling (LOSC), Figure 15-1. Relevant context information for the scenario include: operating instructions for the reactor cooling system including EOPs and other relevant plant procedures, general plant layout, operating experience, design specifications for the system, system-fault information, information about the associated equipment and system functions, etc.

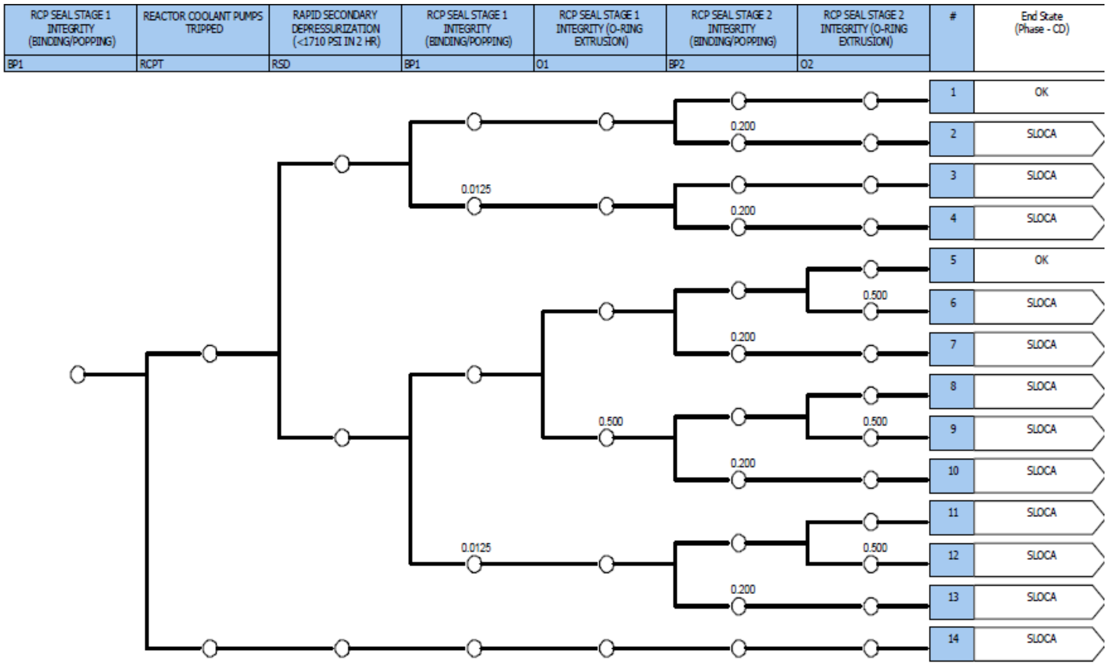


Figure 15-1: Robinson modified LOSC event tree [116]

15.1.1.2 Step 2: Develop the Crew Response Tree (CRT)

This step involves analyzing the crew's task, constructing the CRT, pruning or simplifying it, and inserting any additional HFEs that are identified in process.

Task Analysis

In the precursor analysis [116], the HFEs have already been defined. In our Task analysis, the HFE of interest is the failure of the crew to restore seal injection and cooling to the RCPs. Our task analysis flow is provided by the level of detail in PRA model combined with the CRT, and fault tree representation of our human response model (IDA). We have also defined types of crew activities which guide the entire task analysis process.

According to the PRA model and details of the event given, the reactor has tripped and the crew responded by entering EOP Path-1, step 4. The overall task was to restore seal injection and cooling to the RCPs. This task can be decomposed into two sub-tasks of restoring seal cooling and restoring seal injection. The sub-task of restoring seal cooling in turn involves the following sub-tasks:

- Transfer from EOP Path-1, step 4 to End Path Procedure (EPP 4) to open CCW flow for reactor trip response.
- Use other cues (the RCP thermal barrier cooling water low flow annunciator and bearing high temperature alarms) to open CCW flow.
- Open FCV-626

The sub-task of restoring seal injection in turn involves the following sub-tasks:

- Move from EOP Path-1, step 4 to step for checking charging pump status.
- Close CVC 310A.

This task decomposition can be pictorially represented using a hierarchical structure (Figure 15-2). We have used the types of crew activities defined in our methodology to characterize each sub-task in the lowest level of our task decomposition (Table 15-1 and Table 15-2). Each crew activity can be further described as corresponding to the four main functions of Noticing/ detecting / understanding, Situation assessment / Diagnosis, Decision-making / Response planning, and Action taking. These functions in turn correspond to different IDA phases as indicated in Table 4-3. Hence each sub-task can also be traced back to the corresponding phase (s) of our human response model (IDA). As an example, the sub-task "open FCV-626" (Table 15-1) is characterized by the crew activity of decision and execution can be described as corresponding to the Decision-making / Response planning and Action-taking functions respectively, which fall under the Decision making (D) and Action Taking (A) phases of the human response model.

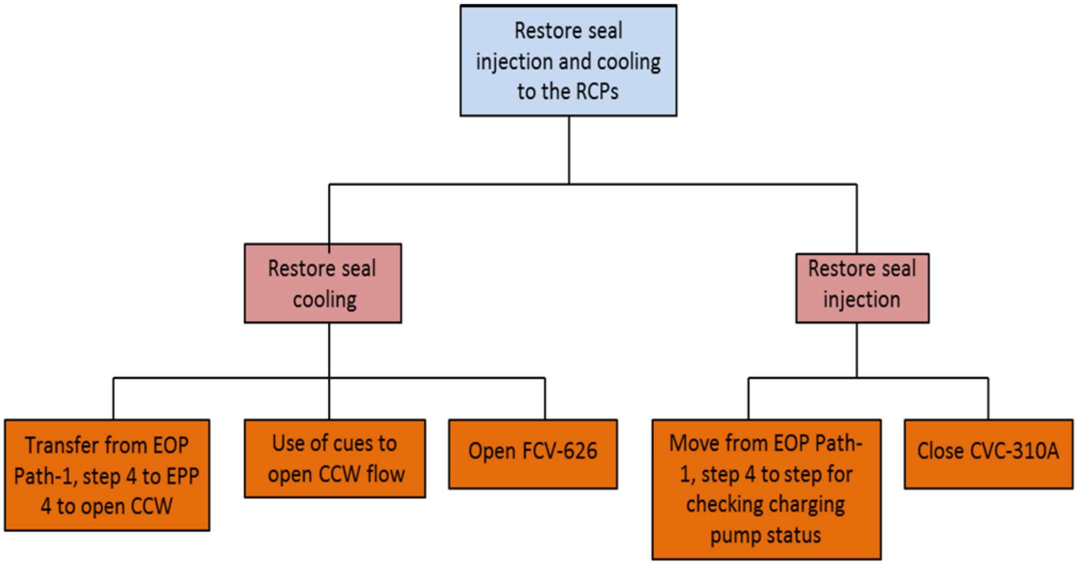
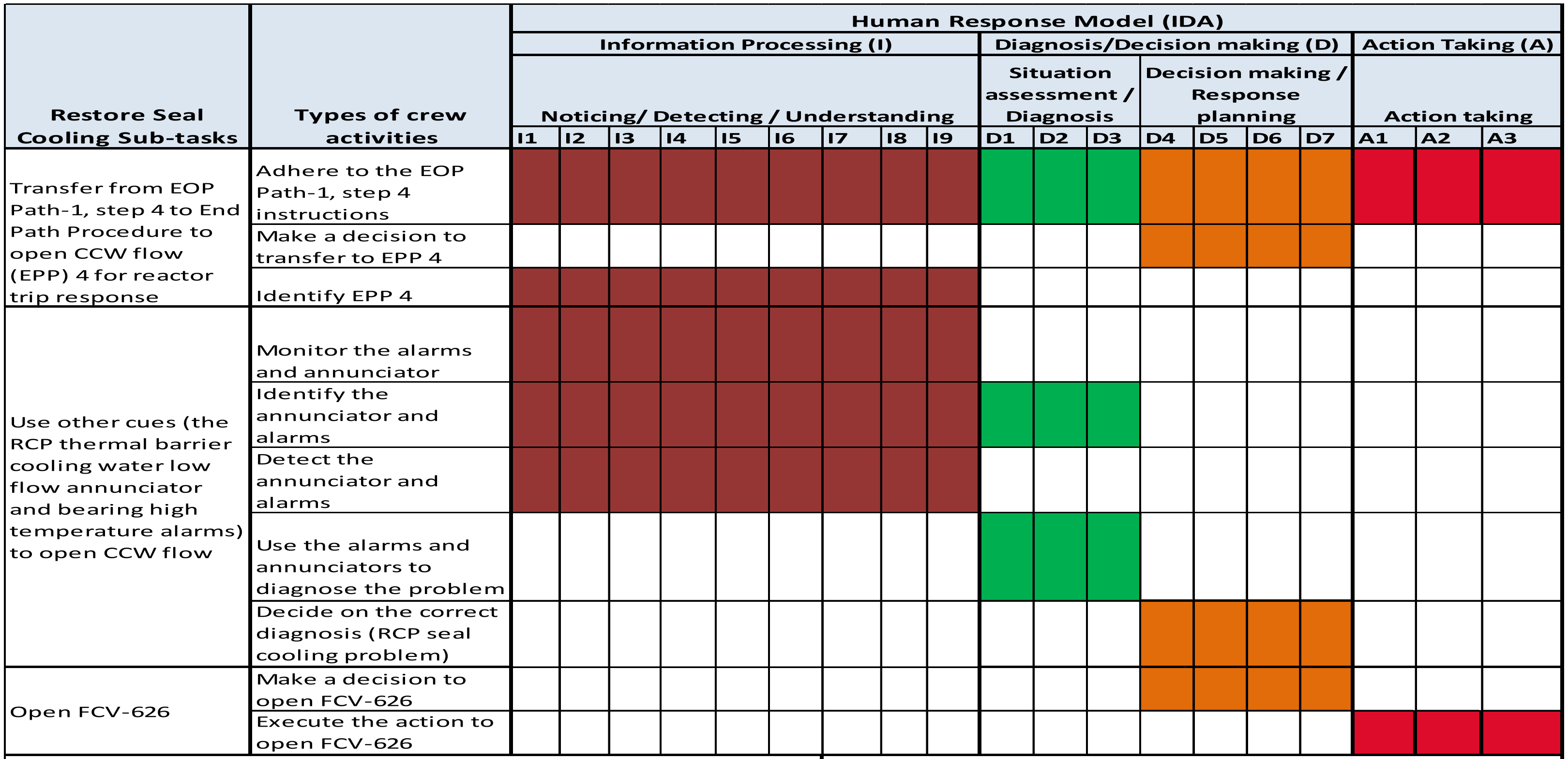


Figure 15-2: Hierarchical structure showing the task decomposition

Table 15-1: Restore seal cooling sub-tasks and corresponding crew activities



Restore Seal Cooling Sub-tasks	Types of crew activities	Human Response Model (IDA)																		
		Information Processing (I)									Diagnosis/Decision making (D)							Action Taking (A)		
		Noticing/ Detecting / Understanding									Situation assessment / Diagnosis			Decision making / Response planning				Action taking		
		I1	I2	I3	I4	I5	I6	I7	I8	I9	D1	D2	D3	D4	D5	D6	D7	A1	A2	A3
Transfer from EOP Path-1, step 4 to End Path Procedure to open CCW flow (EPP) 4 for reactor trip response	Adhere to the EOP Path-1, step 4 instructions	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟥	🟥	🟥
	Make a decision to transfer to EPP 4													🟧	🟧	🟧	🟧			
	Identify EPP 4	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫										
Use other cues (the RCP thermal barrier cooling water low flow annunciator and bearing high temperature alarms) to open CCW flow	Monitor the alarms and annunciator	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫										
	Identify the annunciator and alarms	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩							
	Detect the annunciator and alarms	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫										
	Use the alarms and annunciators to diagnose the problem										🟩	🟩	🟩							
	Decide on the correct diagnosis (RCP seal cooling problem)													🟧	🟧	🟧	🟧			
Open FCV-626	Make a decision to open FCV-626													🟧	🟧	🟧	🟧			
	Execute the action to open FCV-626																	🟥	🟥	🟥

I1: Key Alarm not Responded to (intentional & unintentional)
I2: Data Not Obtained (Intentional)
I3: Data Discounted
I4: Decision to Stop Gathering Data
I5: Data Incorrectly Processed
I6: Reading Error
I7: Information Miscommunicated
I8: Wrong Data Source Attended to
I9: Data Not Checked with Appropriate Frequency

D1: Plant/System State Misdiagnosed
D2: Procedure Misinterpreted
D3: Failure to Adapt Procedure to the situation
D4: Procedure Step Omitted (Intentional)
D5: Inappropriate Transfer to a Different Procedure
D6: Decision to Delay Action
D7: Inappropriate Strategy Chosen
A1: Incorrect Timing of Action
A2: Incorrect Operation of Component/Object
A3: Action on Wrong Component / object

Table 15-2: Restore seal injection sub-tasks and corresponding crew activities

Restore Seal Injection Sub-tasks	Types of crew activities	Human Response Model (IDA)																		
		Information Processing (I)									Diagnosis/Decision making (D)							Action Taking (A)		
		Noticing/ Detecting / Understanding									Situation assessment / Diagnosis			Decision making / Response planning				Action taking		
		I1	I2	I3	I4	I5	I6	I7	I8	I9	D1	D2	D3	D4	D5	D6	D7	A1	A2	A3
Move from EOP Path-1, step 4 to step for checking charging pump status	Make a decision to go to the step for checking charging pump status													🟧	🟧	🟧	🟧			
	Adhere to the instructions given for checking the pump status	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟥	🟥	🟥
	Identify the charging pump	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫										
	Detect /observe the pump status by reading the indicator or other given parameters	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫										
close CVC 310A	Make a decision to close CVC 310A													🟧	🟧	🟧	🟧			
	Execute the action to close CVC 310A																	🟥	🟥	🟥

I1: Key Alarm not Responded to (intentional & unintentional)	D1: Plant/System State Misdiagnosed
I2: Data Not Obtained (Intentional)	D2: Procedure Misinterpreted
I3: Data Discounted	D3: Failure to Adapt Procedure to the situation
I4: Decision to Stop Gathering Data	D4: Procedure Step Omitted (Intentional)
I5: Data Incorrectly Processed	D5: Inappropriate Transfer to a Different Procedure
I6: Reading Error	D6: Decision to Delay Action
I7: Information Miscommunicated	D7: Inappropriate Strategy Chosen
I8: Wrong Data Source Attended to	A1: Incorrect Timing of Action
I9: Data Not Checked with Appropriate Frequency	A2: Incorrect Operation of Component/Object
	A3: Action on Wrong Component / object

CRT Construction

This event can be modeled as having one HFE (failure of the crew to restore seal injection by closing CVC-310A and seal cooling by re-opening FCV-626 to the RCPs) or broken down into different combinations of HFEs. For the purpose of our analysis and in order to be consistent with the actual analysis report [116], we have broken down it down into two HFEs namely:

- Failure of crew to restore CCW to the RCPs by reopening FCV-626, and
- Failure of crew to restore seal injection to the RCPs by closing CVC-310A

Our CRT flow chart methodology covers a case where the HFE is associated with a specific safety function in the context of a defined PRA scenario. Therefore, the event can be associated with two safety functions namely:

- Keep the CCW flow to cool down the thermal barrier of the RCP
- Keep seal injection to the RCP seal

Using the CRT construction flow chart (Figure 5-1) provided, the flow chart questions (Table 5-1) and the description of the Success and Failure Paths for each BP (Table 5-2), we have constructed two CRTs, each representing a safety function and provided corresponding tables to indicate the flowchart questions and branch point descriptions. In addition, we have also demonstrated the concept of the modular construction of CRT where the two different function-level CRTs actually form a larger and more comprehensive CRT.

Safety function 1: Keep CCW flow to cool down thermal barrier of RCP

The preconditions are as follows:

- FCV-626 failed close

- CVC-310A failed open
- Reactor trip, operating crew in EOP Path-1, step 4

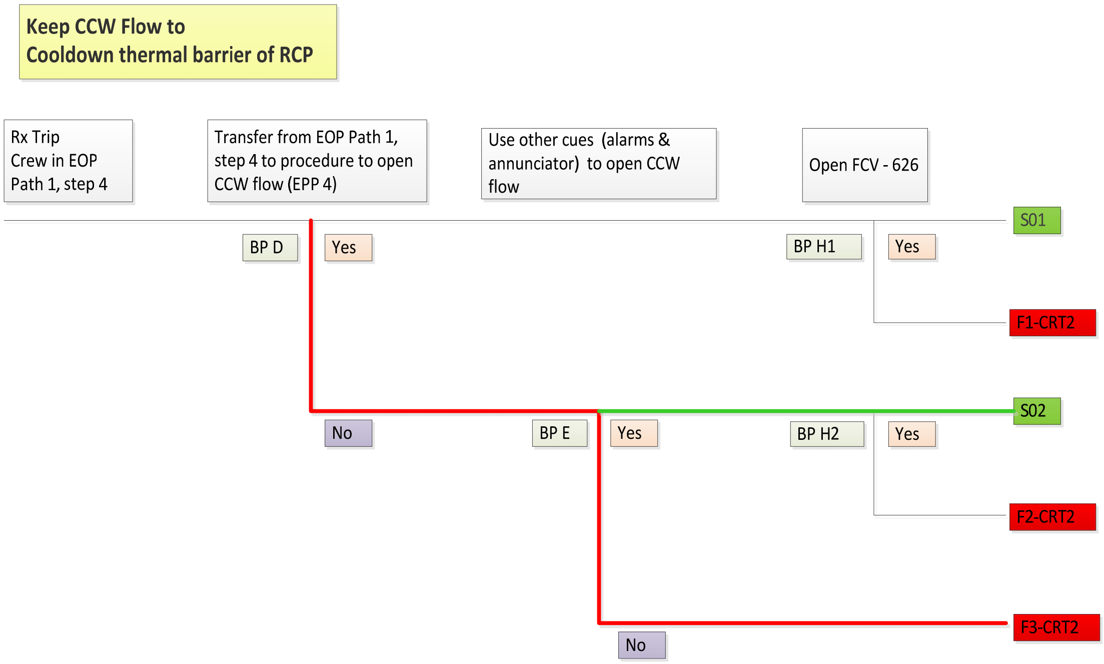


Figure 15-3: CRT 1 for the safety function “keep CCW flow to cool down thermal barrier of RCP”

Note that the sequence from branch point (BP) D through BP E (highlighted in red), BP H2 and ends with the success end state “S02” (highlighted in green) was the actual path taken by the crew during this event. The other paths are all hypothetical. Also, even though all three failure paths BP D to end state F1-CRT2, BP D to end state F2-CRT2, and BP D to end state F3-CRT2 all add up to the HFE (failure of crew to restore CCW to the RCPs by reopening FCV-626), we will be using only the path from BP D to end state F3-CRT2 (highlighted in red) to estimate the HEP for the HFE. This is because the other paths are those of execution error and have a lower probability when compared to that of cognitive error (BP D to end state F3-CRT2).

Table 15-3: Flow chart questions for CRT 1

No.	Question	Answer
1	Is the specific function designed to be initiated automatically?	No, go to question 3.
2	Is the scenario a fast transient?	NA
3.a	Is there a procedure that includes monitoring and operation of the specific safety function?	Yes, procedure to open CCW flow. Go to Branch Point D.
3.b	Is there a specific entry point in the current procedure to a step to manually initiate the safety function?	
4	Are there other procedural entry points that lead to a step to manually initiate the safety function? This could include other cues like alarms, annunciators, shift technical advisor (STA who is always monitoring the control panel)	Yes, using other cues (alarms and annunciator) to open CCW flow). Go to Branch Point E.
5.1	Are there any unexplored options under 3.b and 4?	No, there are no other options in the particular procedure. Go directly to Branch Point H1 because Branch point G is ignored due to the low probability of its occurrence and hence, it is not created in the CRT.
5.2	Are there any unexplored options under 3.b and 4?	No, there are no other options in the particular procedure. Go directly to Branch Point H2 because Branch point G is ignored due to the low probability of its occurrence and hence, it is not created in the CRT.
6.1	Are there additional equipment and manual actions that could be used to provide the specific safety function? This question refers to recovery actions that the crew could potentially take when everything else fails.	No, there are no other ways to achieve the safety function (failed path, go to F1-CRT 2).
6.2	Same as 6. 1	No, there are no other ways to achieve the safety function (failed path, go to F2-CRT 2).

Table 15-4: Description of success and failure paths for each BP in CRT 1

BP	Description	Application in CRT
A	Crew manually initiates the safety function before it is automatically initiated.	NA
B	The safety function is automatically initiated.	NA
C	Crew does not manually turn off the automatically initiated safety function.	NA
D	This branch point considers whether the crew is in the correct procedure, various options provided by the procedure for success (i.e., multiple choices, each providing a successful path to the critical step to manually initiate the safety function, given the condition) So this branch point may produce multiple branches, each of which need to be pursued separately in the CRT. The Success Path corresponds to operator choosing a correct option for the condition and manually initiating the safety function.	Branch Point: Transfer from EOP step 4 to EPP 4 (procedure to open CCW flow). • Success Path – Yes, crew transfer to EPP 4 (Go to Question 5). • Failure Path – No, crew doesn't transfer to EPP 4 (Go to Question 4).
E	Similar to Branch Point D.	Branch Point: Use other cues (RCP thermal barrier cooling water low flow annunciator and bearing high temperature alarms) to open CCW flow. • Success Path – Yes, crew uses other cues to open CCW flow (Go to Question 5). • Failure Path – No, crew doesn't use other cues to open CCW flow (Failed path, go to F3-CRT 2).
F	Crew doesn't transfer to the wrong direction from the exit point.	NA
G	Safety function is not impaired by equipment (hardware / system) failure.	This BP is ignored because of the low probability of this event. Therefore this BP is not created (go directly from Question 5 to Branch point H).
H1	Crew successfully initiates the safety function manually.	Branch Point: Open FCV-626. • Success Path – Yes, crew opens FCV-626 (success path SO1). • Failure Path – No, crew doesn't open FCV-626 (go to Question 6).
H2	Crews successfully initiate the safety function manually.	Branch Point: Open FCV-626. • Success Path – Yes, crew opens FCV-626 (success path SO2). • Failure Path – No, crew doesn't open FCV-626 (go to Question 6).

Safety function 2: Keep seal injection to RCP seal

The preconditions are as follows:

- FCV-626 failed close
- CVC-310A failed open
- Failed CRT 1 sequences i.e. F1-CRT2, F2-CRT2, and F3-CRT2

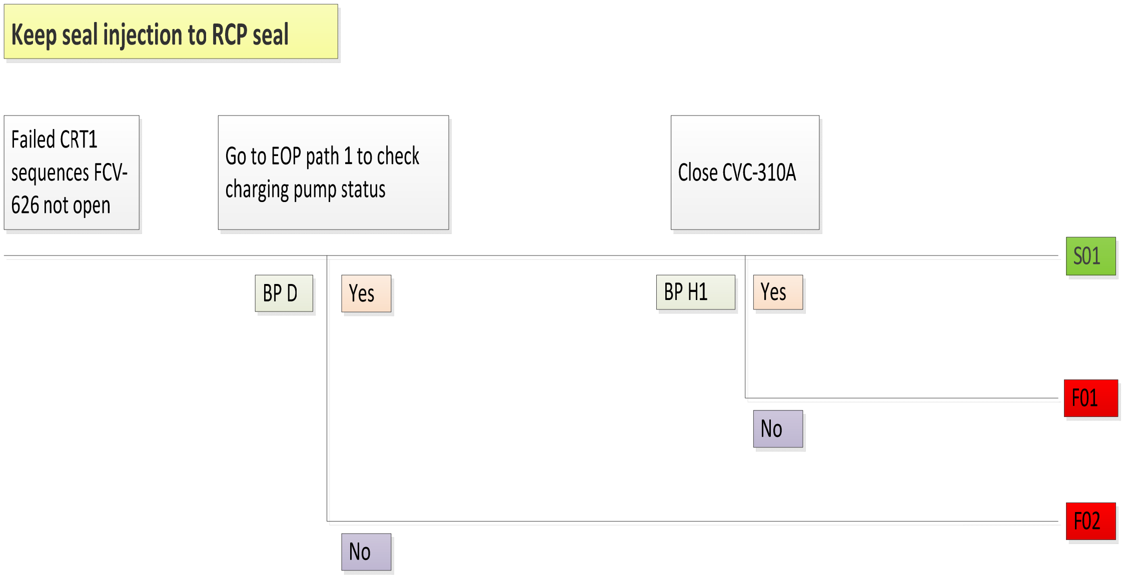


Figure 15-4: CRT 2 for the safety function "keep seal injection to RCP seal"

Table 15-5: Flow chart questions for CRT 2 (keep seal injection to RCP seal)

No.	Question	Description and Example
1	Is the specific function designed to be initiated automatically?	No, go to question 3.
2	Is the scenario a fast transient?	NA
3.a	Is there a procedure that includes monitoring and operation of the specific safety function?	Yes, EOP path 1. Go to Branch Point D.
3.b	Is there a specific entry point in the current procedure to a step to manually initiate the safety function?	
4	Are there other procedural entry points that lead to a step to manually initiate the safety function?	No, there is no extra entry point in the procedure to check charging pump status. Failed path F02.
5	Are there any unexplored options under 3.b and 4?	No, there are no other options in the particular procedure. Go directly to Branch Point H because Branch point G is ignored due to the low probability of its occurrence and hence, it is not created in the CRT.
6	Are there additional equipment and manual actions that could be used to provide the specific safety function? This question refers to recovery actions that the crew could potentially take when everything else fails.	No, there are no other ways to achieve the safety function (Failed path F01).

Table 15-6: Description of success and failure paths for each BP in CRT 2

BP	Description	Application in CRT
A	Crew manually initiates the safety function before it is automatically initiated.	NA
B	The safety function is automatically initiated.	NA
C	Crew does not manually turn off the automatically initiated safety function.	NA
D	This branch point considers whether the crew is in the correct procedure, various options provided by the procedure for success (i.e., multiple choices, each providing a successful path to the critical step to manually initiate the safety function, given the condition) So this branch point may produce multiple branches, each of which need to be pursued separately in the CRT. The Success Path corresponds to operator choosing a correct option for the condition and manually initiating the safety function.	Branch Point: Go to EOP path 1 to check charging pump status. • Success Path – Yes, crew goes to EOP path 1 to check charging pump status (Go to Question 5). • Failure Path – No, crew doesn't go to EOP path 1 to check charging pump status (Go to Question 4).
E	Similar to Branch Point D.	NA
F	Crew doesn't transfer to the wrong direction from the exit point.	NA
G	Safety function is not impaired by equipment (hardware / system) failure.	This BP is ignored because of the low probability of this event. Therefore this BP is not created (go directly from Question 5 to Branch point H).
H	Crew successfully initiates the safety function manually.	Branch Point: Close CVC -310A. • Success Path – Yes, crew closes CVC – 310A (success path SO1). • Failure Path – No, crew doesn't close CVC – 310A (go to Question 6).

Note that the CRT doesn't need to be pruned and for the purpose of this example, there are no HFEs to add to the PRA model.

15.1.1.3 Step 3: Identify CFMs for CRT branches

The scenario leading to the HFE of interest (failure of crew to restore CCW to the RCPs by reopening FCV-626) has end state F3-CRT2 in CRT1. It has two branch points BP D (transfer from EOP Path 1, step 4 to EPP 4) and BP E (use other cues to open CCW flow).

BP D - Transfer from EOP Path 1, step 4 to EPP 4

According to the precursor report [116], when the crew got to EOP Path 1, step 4, they were unsure of what had happened and they didn't do anything. They basically waited at that point for more information and delayed transferring to EPP 4. They finally didn't transfer to EPP 4. That means that the conditional failure probability for BP D is 1.

However, let's assume a hypothetical case where we are not sure if they transferred to EPP 4. We will be relating it to the (D) phase of our fault tree model which represents our human response (IDA) model. This means that the crew failed in making the decision to transfer to EPP 4 even when the procedure told them to do so. Tracing through the D part of the fault tree model while following procedure as the strategy, the predominant CFMs are *Decision to delay action* (D6) because they were waiting for more information, *Inappropriate strategy chosen* (D7) because they decided to wait for more information, and *Plant /system state misdiagnosed* (D1) because they were unsure of what had happened (state of the plant). Note that the relevant parts of the fault trees are indicated using red lines and the CFMs have red circles underneath them. Also the predominant CFMs are a subset of those identified as possible CFMs for this task using our task analysis process.

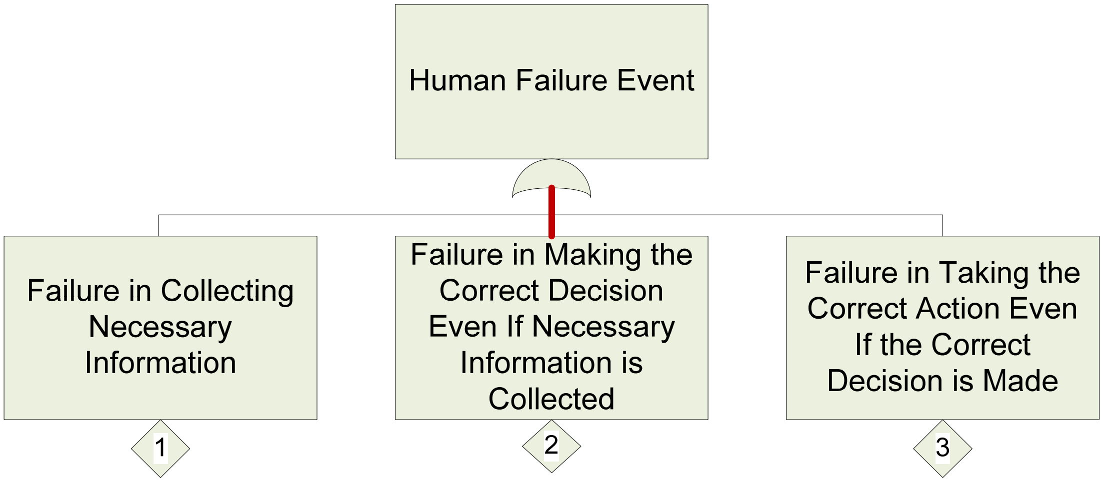


Figure 15-5: HFE logic with phase D as the relevant one for BP D in CRT1

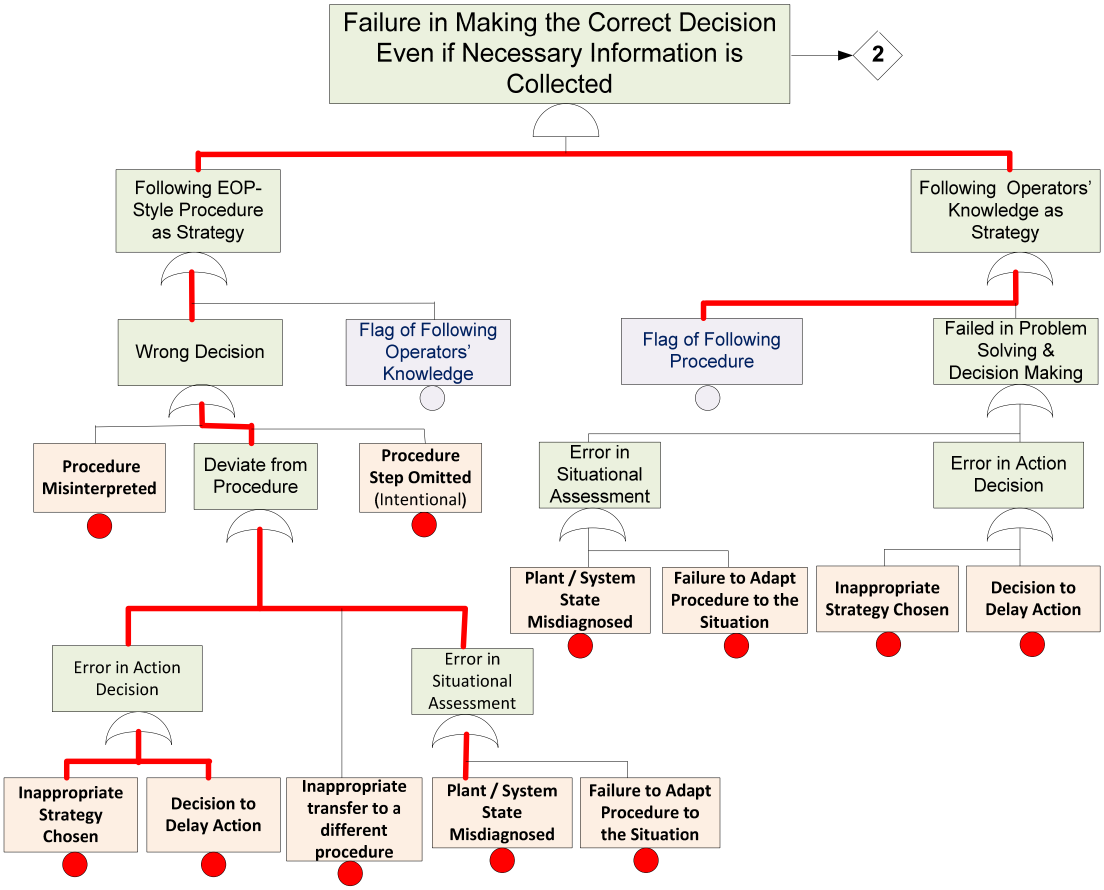


Figure 15-6: D phase part of the FT showing the relevant sections and CFMs for BP D in CRT1

BP E - Use other cues (alarms & annunciator) to open CCW flow

For this precursor analysis, we are assuming that the crew did not follow the cues to check the annunciator or the alarms (even though they did in reality). In relation to the human response fault tree model, there was a failure in collecting necessary information (I). Tracing through the I phase of the fault tree model, the crew failed in decision to collect necessary information. While following procedure as the strategy, the predominant CFMs are *Data not obtained* (I2) because they were focused on procedure and had no experienced crew member available in the control room at the time, and *Data not checked with appropriate frequency* (I9) because they didn't check the annunciator or alarms as required. Note that the relevant parts of the fault tree are also indicated using red lines. Also the predominant CFMs are a subset of those identified as possible CFMs for this task using our task analysis process.

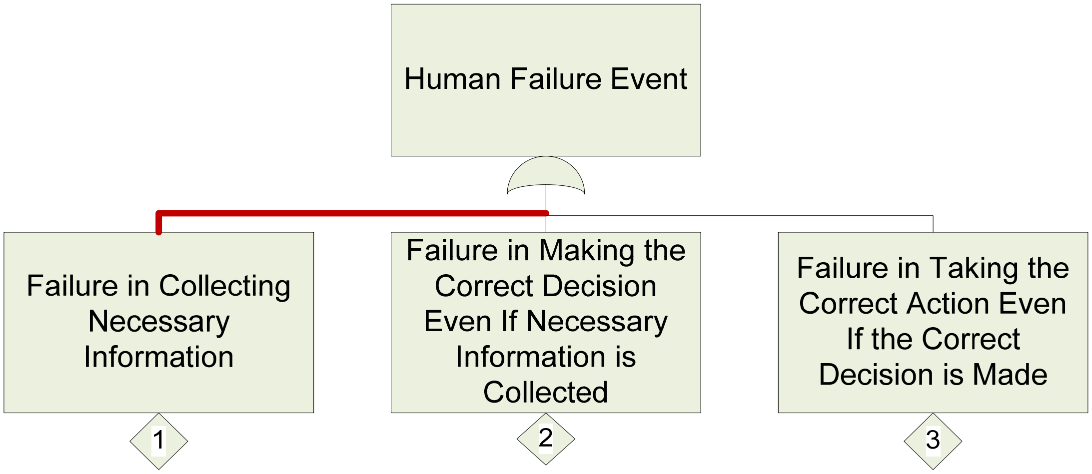


Figure 15-7: HFE logic with phase I as the relevant one for BP E in CRT1

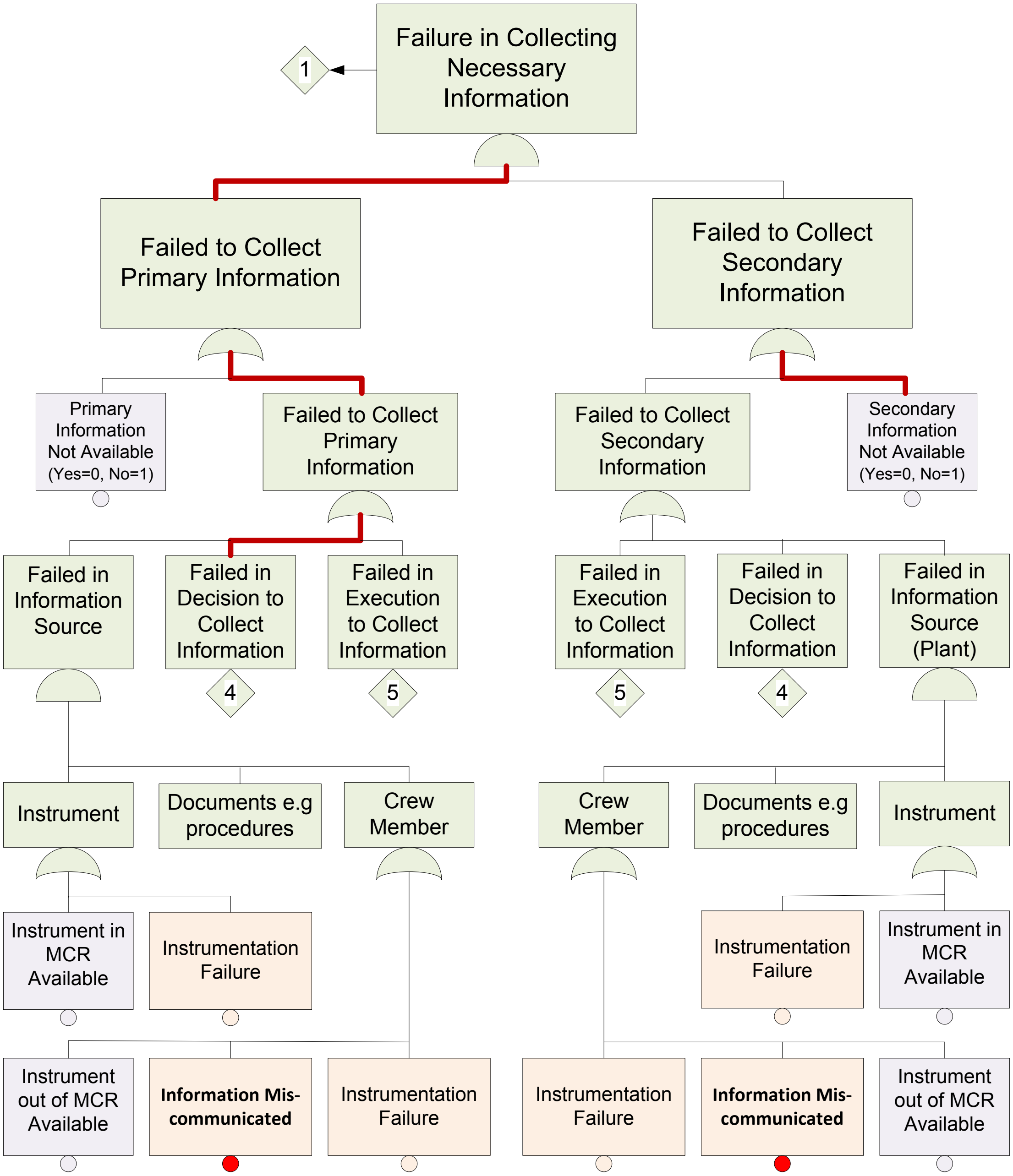


Figure 15-8: Phase 1 part of the FT continued for BP E in CRT 1

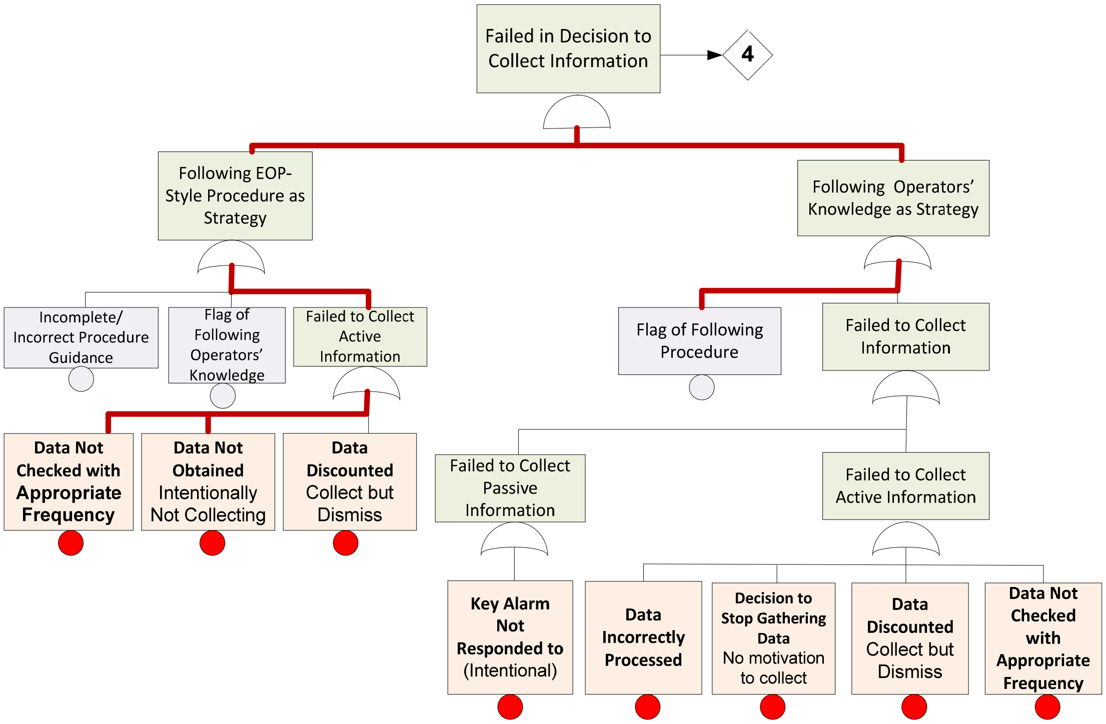


Figure 15-9: Decision in I phase part of the FT showing the relevant sections and CFMs for BP E in CRT1

15.1.1.4 Step 4: Develop CRT scenarios for HFE (s)

This step involves the development of the CRT scenarios for HFE in terms of CFMs cut-sets and also the identification of the PIFs relevant to the CRT scenario.

<u>CRT scenario CFM minimal cut-sets</u>

In order to obtain the CFM Cut-sets for the HFE scenario of interest, the FTs (Figure 15-5 to Figure 15-9) have to be linked to the respective BPs and each BP is expressed in terms of its CFM logic. Then using the ET logic, they can be combined to produce the cut-sets for the scenario.

For the hypothetical case which assumes that we are not sure if the crew transferred to EPP 4, then for BP D, the minimal CFM cut-sets are D1, D6, D7, and expressed as D1+D6+D7. For BP E, the minimal CFM cut-sets are I2, I9, expressed as I2+I9. Hence, for the entire scenario, the CFM minimal cut-set expression (CFM min cut_{hypo}) is given as follows:

CFM min cut_{hypo} = (D1+D6+D7)*(I2+I9) = I2D1+I2D6+I2D7+I9D1+I9D6+I9D7

For the real case (which the crew did not actually transfer to EPP 4), the probability of failure given BP D is 1. In this case, the CFM min cut_{real} for the entire scenario is given by:

CFM min cut_{real} = I2 + I9

Identification of relevant PIFs

Given the event, the following PIFs have been identified as relevant, i.e. PIFs that influenced the crew performance by degrading it. We have identified these PIFs as the dominant ones, even though it may be argued that there are other PIFs relevant to the scenario.

- *Procedure Quality*: The EOP which the crew was using didn't contain instructions that directed them to check CCW status. It was only the alarm response procedure (ARP) that addressed it. As a side note (since this is not directly related to this HFE but to the failure to restore seal injection to RCP by closing CVC-310A), the EOP directed the crew to check the status of the charging pump and not the status of the flow rate of the pump (which should be what the crew needed to check). Therefore, the crew checked the pump status and it was running. However, there was no flow because the pressure release valve (CVC 310A) had opened and the crew was unaware of it.
- *Leadership*: According to [116], "the crew supervisors were distracted from oversight of the plant including the awareness of major plant parameters and

failed to properly manage the frequency and duration of crew updates/briefs during the early portion of the event leading to interruption in the implementation of emergency procedures and distraction of the crew." Therefore the crew didn't have adequate leadership and wasn't properly supervised during the event because their supervisors were attending to other issues that had occurred earlier in the plant.

- *Team Composition*: According to the report, the team composition was determined to be less than optimal because several crew members were newly qualified or were standing unfamiliar or new positions. Also, the most experienced reactor operator was stationed as the balance-of-plant operator and was busy with fire-related activities that had occurred earlier in the plant and was not actively supporting the initial reactor plant response.
- *Extra Work Load:* Due to the fire event that occurred earlier in the plant, the crew had other tasks to perform in addition to responding to this event.
- *Knowledge/Experience/Skill (content):* The simulator training which the crew underwent was not a true representation of the actual control room which they work in. According to [116], "the plant's training simulator did not demonstrate the correct expected plant response for a loss of Instrument Bus 4. Specifically, the operating crews experience in simulator training was for FCV-626 to stay open during a loss of Instrument Bus 4." Hence, they did not have the adequate knowledge/experience/skill level required for this event.
- *Cognitive Complexity*: There was a fire in the plant and it rendered several electric buses unavailable. The crew needed to restore electricity and then CVC-310A

opened, causing diverse flow which in turn caused inadequate seal cooling. The occurrence of these multiple failures in the plant induced high cognitive demands on the crew.

- *Time Constraint*: According to [116], “the crew would need minimal time (< 1 minute) to re-open FCV-626 from the control room. Based on the RCP purge volumes (48 gallons) and the seal leak-off rates and temperatures of RCP B, they would only have approximately 19 minutes to determine the need to restore RCP seal cooling. The crew was unaware that CCW to the RCPs was isolated via FCV-626 until the second RCP bearing high temperature alarm was received (approximately 13 minutes after seal injection had become inadequate). Therefore, only 6 minutes was available for operators to diagnose the need to reopen FCV-626 prior to voiding conditions within RCP B.” Hence, the amount of time they had available was also a factor.

15.1.1.5 Step 5: Analyze Scenarios, Write Narrative, Trace Dependencies

The path through the integrated model (PRA, CRT, FTs and BBN) gives the details of how the entire story needs to be narrated and read. For the real case (which the crew did not actually transfer to EPP 4), the scenario of interest (F3-CRT1), in made up of 2 sub-scenarios (I2 and I9).

For the hypothetical case (which assumes that we are not sure if the crew transferred to EPP 4), the scenario of interest (F3-CRT1) is made up of 6 sub-scenarios namely: I2D1, I2D6, I2D7, I9D1, I9D6, and I9D7. In either the real or hypothetical case, these sub-scenarios are strings and when combined together, contribute to the entire story.

Beginning with the event, loss of reactor coolant pump (RCP) seal injection and cooling, the crew needed to either open FCV-626 to restore CCW to the RCP seals or close CVC-310A to restore charging flow to the RCP seals. Either of these actions needed to be carried out within 13 minutes of the loss of seal cooling and seal injection. Therefore the crew had the task of restoring seal cooling and injection to the RCP seals. This task could be decomposed into two main sub task of restoring seal cooling and restoring seal injection. Each of this sub tasks has been further decomposed into more sub tasks, corresponding crew activities and functions (Table 15-1 and Table 15-2).

Therefore, for the HFE scenario (failure of crew to restore seal cooling to the RCPs), the crew could fail due to any of the following reasons:

Real case:

- They did not obtain the information from the annunciator /alarms
- They did not check the annunciator / alarms at the appropriate time

Hypothetical case:

- They did not obtain the information from the annunciator /alarms and hence, misdiagnosed the state of the system (corresponds to I2D1 CFM combination).
- They did not obtain the information from the annunciator /alarms and hence, decided to delay and wait for more information (corresponds to I2D6 CFM combination).
- They did not obtain the information from the annunciator /alarms and hence, decided to choose a strategy that was inappropriate i.e. they did not follow the procedure instructions (corresponds to I2D7 CFM combination).

- They did not check the annunciator / alarms at the appropriate time and hence, misdiagnosed the state of the system (corresponds to I9D1 CFM combination).
- They did not check the annunciator / alarms at the appropriate time and hence, decided to delay and wait for more information (corresponds to I9D6 CFM combination).
- They did not check the annunciator / alarms at the appropriate time and hence, decided to choose a strategy that was inappropriate i.e. they did not follow the procedure instructions (corresponds to I9D7 CFM combination).

Also, these crew failures were enhanced by the inadequate quality of the procedure, extra work load imposed on them by other plant events, inadequate leadership during the event, less than optimal team make up, inadequate knowledge/experience/skill level of the crew, cognitive demands induced on them by the occurrence of multiple failures within a short span of time, and the limited amount of available time which was barely enough for the tasks.

Inputs to quantification

The inputs to the quantitative analysis are as CFM minimal cut-set logic expression (I2 + I9) for the real case, or (I2D1+I2D6+I2D7+I9D1+I9D6+I9D7) for the hypothetical case. The inputs also include the list of relevant PIFs mapped to the main PIF groups (Procedures, Team effectiveness, Task load, Knowledge/abilities, and Time Constraint).

15.1.2 Quantitative Analysis – Phoenix HRA

The quantitative analysis will be carried out by applying the methodology steps. Note that the BBN model for this example is built and run using IRIS [84] and GeNie [90] softwares.

15.1.2.1 Step 1: Identify the CFMs in the BBN model

This step involves the identification of the relevant and non-relevant CFMs in the model. They are I2, I9 for the real case, and I2, I9, D1, D6, D7 for the hypothetical case. All the other CFMs are considered non-relevant and we have incorporated this information into the model. This is done by changing all the conditional probabilities for the failure state of each CFM to 0 (zero) i.e. all the conditional probabilities on the failure row (the 10 conditional probabilities including the leak factor) in the BBN model, and all the conditional probabilities for the success state of each CFM to 1 (one) i.e. all the conditional probabilities on the success row (the 10 conditional probabilities including the leak factor) in the BBN model as well.

15.1.2.2 Step 2: Identify PIFs in the BBN model

This step involves the identification of the relevant and non-relevant PIFs in the model. The relevant PIFs are Procedures, Team effectiveness, Knowledge/Abilities, Task load and Time Constraint. All the other PIFs are considered non-relevant and we have incorporated this information into the model. This is done by changing all the levels for the nominal state of the PIF (marginal probability) to 1 (one), and all the levels for the degraded state of the PIF (marginal probability) to 0 (zero).

15.1.2.3 Step 3: Assess the Relevant PIF levels

This step involves the assessment of the relevant PIF levels and the incorporation of the information into the model.

PIF level assessment

This is done using the tables provided for each of these PIFs in section 12.3.1.

Procedures

Using the PIF assessment questionnaire for *Procedures* (Table 15-7), the PIF level for the degraded state (inadequate procedures) is estimated to be 0.7.

Table 15-7: PIF assessment - Procedures

Procedures					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Are the required procedures unavailable?	Procedure availability		X	
2	Does the primary procedure (i.e. the main procedure being used) lack all the necessary instructions?	Procedure quality	X		
3	Is there a Procedure-Scenario Mismatch i.e. the plant conditions do not match procedure assumptions?	Pocedure quality		X	
4	Does the procedure provide conflicting guidance ?	Procedure quality		X	
5	Are there confusable words included in the procedures such as "increase" and "decrease"?	Procedure quality		X	
6	Is the procedure ambiguous in its meaning? If the steps are not clear or lack details for the desired action in the context of the sequence of interest, then the procedure is ambiguous. A procedure may also be judged as being ambiguous if acceptance / success criteria and tolerances or specific control positions and indicator value are not properly specified.	Procedure quality		X	
7	Does the procedure contain double-negatives?	Procedure quality		X	
8	Are charts, graphs, or figures within the procedure difficult to read or understand?	Procedure quality		X	
9	Does the procedure prompt a situation in which the crew is required to perform calculations or make other manual adjustments without the aid of worksheets?	Procedure quality		X	
	Total		**1**	**8**	
	Flag 1: If the answer to question 1 is Yes, then set the level of the degraded state of the PIF to 1. there is no need to continue going through the questions.				
	Flag 2: If the answer to question 1 is No and the answer to question 2 is Yes, then the level of the degraded state of the PIF = 0.7 + (Total no. of Yes -1)/(Total no. of Yes + No -2). Note that if (Total no. of Yes - 1)/(Total no. of Yes + No -2) is greater than 0.3, it should be normalized to 0.3.	**0.7**			
	If the answer to questions 1and 2 is No, then, estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Team Effectiveness

Using the PIF assessment questionnaire for *Team Effectiveness* (Table 15-8), the PIF level for the degraded state (ineffective team) is estimated to be 0.6.

Table 15-8: PIF assessment – Team Effectiveness

Team Effectiveness					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Does the crew have limited experience in working together?	Team coordination	**X**		
2	Is there tight communication/coordination demands?	Communication availability	**X**		
3	Does the required verbal communication include similar sounding words, e.g., “increase” and “decrease”?	Communication quality		**X**	
4	Is the crew lead likely to assume that unsupervised work is sufficient (misplaced trust)?	Leadership		**X**	
5	Is the crew lead too involved in individual tasks (over focused)?	Leadership	**X**		
6	Is the crew lead overconfident?	Leadership		**X**	
7	Are the crew members non-confrontational, i.e., are they disinclined to confront nonconformance?	Team cohesion		**X**	
8	Does the crew have a cohesion problem i.e., baggage or historical issues	Team cohesion		**X**	
9	Are there crew members that are unclear about their responsibilities or duties within the group?	Role Awareness		**X**	
10	Is there a shortage of personnel required to make up the crew?	Team composition	**X**		
11	Is there a challenging mix of experience within the crew?	Team composition	**X**		
12	Is the crew lacking the training to work together?	Team training	**X**		
13	Is the required equipment (telephone, walkie-talkie, etc.) unavailable or degraded to the point that the message becomes ambiguous or interferes with communication?	Communication quality		**X**	
14	Is there excess noise in the local, ex-control room environment that degrades the quality, clarity or volume of the message?	Communication quality		**X**	
15	Are there factors (e.g.,excess noise, steam, temperature) that affect the ability of the crew to correctly obtain the required information?	Communication quality		**X**	
16	Do both the speaker and the receiver use non-standard terminology /improper communications protocol (not using established plant communication protocols and, in particular, not using two or three way repeat-back to confirm the receipt of the correct information?	Communication quality		**X**	
	Total		**6**	**10**	
	Flag: If the answer to question 1 is Yes, then the level of the degraded state of the PIF = 0.3 + (Total no. of Yes -1)/(Total no. of Yes + No -1). Note that if (Total no. of Yes -1)/(Total no. of Yes + No -1) is greater than 0.7, it should be normalized to 0.7.	**0.3 + 0.3 = 0.6**			
	If the answer to questions 1 is No, then, estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).				

Knowledge/Abilities

Using the PIF assessment questionnaire for *Knowledge / Abilities* (Table 15-9), the PIF level for the degraded state (inadequate knowledge / abilities) is estimated to be 0.88.

Table 15-9: PIF assessment – Knowledge / Abilities

Knowledge / Abilities					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Is it likely that crew form a wrong mental model of the situation?	Knowledge / Experience / Skill (Content)	X		
2	Does the crew lack the required knowledge or experience/skill?	Knowledge / Experience / Skill (Content)	X		
3	Does the crew lack the training required to detect alarm / system malfunctions?	Task Training	X		
4	Does the crew lack the training required to detect recognizable patterns that point to the system problem?	Task Training	X		
5	Is the crew unfamiliar with the task?	Task Training	X		
6	Is there a tendency to fail to adhere to STAR (stop, think, act, and review)?	Knowledge / Experience / Skill (Access)	X		
7	Is the crew likely to have multiple competing demands on their attention?	Attention	X		
8	Is the crew slow in thinking, moving, monitoring, and communication?	Physical Abilities and Readiness		X	
	Total		**7**	**8**	
	Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).	**7/8 = 0.88**			

Task load

Using the PIF assessment questionnaire for *Task Load* (Table 15-10), the PIF level for the degraded state (inadequate task load) is estimated to be 0.75.

Table 15-10: PIF assessment – Task Load

Task Load					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Is the inherently complex nature of the problem being solved likely to induce cognitive demands on the crew?	Inherent cognitive complexity	X		
2	Are there external situational factors and conditions that would induce cognitive demands on the crew?	Cognitive complexity external to the mind	X		
3	Is the inherently complex nature of the problem being solved likely to induce physical demands on the crew?	Inherent execution complexity		X	
4	Are there external situational factors and conditions that would induce physical demands on the crew?	Execution complexity external to the mind	X		
5	Are there extra work that has to be performed in addition to the main tasks e.g. making and answering phone calls while performing the task at hand?	Extra workload	X		
6	Is the crew presented with multiple information and cues at the same time?	Passive information load	X		
7	Does the task require skillful coordination of separate manipulations?	Execution complexity	X		
8	Are there steps which if reversed could cause a failure of the response (e.g., by damaging equipment)?	Execution complexity		X	
	Total		**6**	**8**	
	Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).	**6/8 = 0.75**			

Time Constraint

Using the PIF assessment questionnaire for *Time Constraint* (Table 15-11), the PIF level for the degraded state (high time constraint) is estimated to be 0.67.

Table 15-11: PIF assessment – Time Constraint

Time Constraint					
ID	**Questions**	**Lower level PIF**	**Yes**	**No**	**N/A**
1	Does the task have to be completed expeditiously as opposed to a more leisurely pace with ample opportunity for checking?	Time constraint		X	
2	Is the crew expected to complete this task simultaneously with other assigned task?	Time constraint	X		
3	Is the task complex (in the sense of requiring a number of different activities within a relatively short time)?	Time constraint	X		
4	Does the specific scenario involve a time margin that is significantly less than those typically trained on?	Time constraint	X		
5	Is the timing of the scenario development such that the conditions for initiation of this action are reached before the other competing actions?	Time constraint		X	
6	Does the need for this response occur when other tasks or procedures are being employed (or the crew needs to respond to several things)? In other words, are multiple functions being challenged at the same time?	Time constraint	X		
	Total		**4**	**2**	
	Estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).	**4/6 = 0.67**			

Note that the analyst may change their assessment of the PIF levels as they go through the scenario, especially in instances where a CFM occurs at multiple BPs. This information is incorporated into the BBN model in the form of evidence for that particular PIF node, by either changing the levels of its states or by instantiating the PIF node to the appropriate state.

Incorporating the estimated PIF levels into the model

After assessment of the PIF levels, the estimates obtained need to be incorporated into the model. This information is incorporated into the model by changing all the levels for both the nominal and degraded states of each PIF (marginal probability) to reflect the respective estimated probabilities. Note that the estimate of the respective levels of each PIF state will be a number between 0 and 1, and when the level for both states of a PIF are added together, it must equal 1.

15.1.2.4 Step 4: Estimate the joint conditional probability of each relevant CFM

This step involves determining the temporal ordering of the CFMs and following the proper procedure to estimate the joint conditional probability of each. For this analysis, we will demonstrate both the non-dependency and dependency quantification.

Non-dependency quantification

In this case, the assumption is that the CFMs are quantified without considering dependency. Therefore, conditional independence is assumed. Using IRIS [84] and GeNie [90] software, we ran the model and obtained the following estimates for the joint conditional probability of each of the relevant CFMs (Table 15-12).

Table 15-12: Joint conditional probabilities of the relevant CFMs

ID	CFMs	Joint conditional Failure probability
I2	Data Not Obtained (Intentional)	4.00E-02
I9	Data Not Checked with Appropriate Frequency	1.20E-02
D1	Plant/System State Misdiagnosed	4.00E-02
D6	Decision to Delay Action	6.00E-03
D7	Inappropriate Strategy Chosen	1.10E-02

Dependency quantification

We will be using the hypothetical case, which assumes we are not sure of the crew's transfer to EPP 4, to demonstrate our dependency modeling and quantification methodology. In this case, dependency between the CFMs is considered. Also, based on the IDA model and the CFM cut-set combination, we are assuming that the CFMs I2 and I9 occur before CFMs D1, D6, and D7.

Number of temporal order (time steps)

Each CFM cut-set (note that there are 6 cut-sets) requires two time steps. However, we need a total of 8 time steps (I2, D1|I2, D6|I2, D7|I2, I3, D1|I3, D6|I3, and D7|I3) instead of 12. This is because I2 and I9 each account for 3 time steps respectively.

Incorporate evidence into the model at the respective time steps

This is known at Bayesian updating. It is done before running the model at each time step to obtain the joint conditional probability of each relevant CFM in the model.

I2 time step

At this time step, the conditional probability of failure of each of the other relevant CFMs is assumed to be 0 (i.e. they haven't occurred and the conditional probability of success is assumed to be 1). To incorporate this information into the model at this time step, all the conditional probabilities for the failure state of each of these other relevant CFMs are changed to 0 (all the conditional probabilities on the failure row i.e. the 10 conditional probabilities), and all the conditional probabilities for the success state changed to 1 (all the conditional probabilities on the success row i.e. the 10 conditional probabilities). Note that the conditional probabilities of the other relevant CFMs are now the same as those of the non-relevant CFMs that were already incorporated into the model in step 1 of the quantitative analysis.

D1|I2 time step

At this time step, it is assumed that I2 has occurred i.e. its conditional probability of failure is 1. This information is incorporated into the model by setting evidence of I2 at this time step to failure. In GeNie [90] or IRIS [84] software, this is done by right clicking node I2, then selecting “evidence”, then “failure”. Also, the conditional probability of failure of each of the other relevant CFMs is assumed to be 0 and incorporated into the model.

D6|I2 time step

At this time step, it is assumed that I2 has occurred i.e. its conditional probability of failure is 1. Also, the conditional probability of failure of each of the other relevant CFMs is assumed to be 0. All these information are then incorporated into the model.

D7|I2 time step

At this time step, it is assumed that I2 has occurred i.e. its conditional probability of failure is 1. Also, the conditional probability of failure of each of the other relevant CFMs is assumed to be 0. All these information are then incorporated into the model.

I9 time step

At this time step, the conditional probability of failure of each of the other relevant CFMs is assumed to be 0 and the information is incorporated into the model.

D1|I9 time step

At this time step, it is assumed that I9 has occurred i.e. its conditional probability of failure is 1. Also, the conditional probability of failure of each of the other relevant CFMs is assumed to be 0. All these information are then incorporated into the model.

D6|I9 time step

At this time step, it is assumed that I9 has occurred i.e. its conditional probability of failure is 1. Also, the conditional probability of failure of each of the other relevant CFMs is assumed to be 0. All these information are then incorporated into the model.

D7|I9 time step

At this time step, it is assumed that I9 has occurred i.e. its conditional probability of failure is 1. Also, the conditional probability of failure of each of the other relevant CFMs is assumed to be 0. All these information are then incorporated into the model.

Joint conditional probabilities of the relevant CFMs

We ran the model at each of the time steps and obtained the following estimates for the joint conditional probability at each of the respective time steps (Table 15-13).

Table 15-13: Joint conditional probabilities obtained at the each time step

Time Steps	Joint conditional failure probability
I2	4.00E-02
I9	1.20E-02
D1|I2	4.20E-02
D6|I2	7.00E-03
D7|I2	1.20E-02
D1|I9	4.20E-02
D6|I9	7.00E-03
D7|I9	1.20E-02

15.1.2.5 Step 5: Estimate the conditional HEP for the HFE

This is the final step in the quantification process which involves the incorporation of the joint conditional probability estimates of the relevant CFMs into the logic equation of the CFM cut-sets in order to obtain the estimated HEP for the HFE.

HEP estimate using the non-dependency quantification procedure

This is used when conditional independence is assumed. For the real case which the crew did not transfer to EPP 4, the conditional HEP estimate is given by ($\mathrm{HEP}_{\mathrm{real}}$):

$$P(I2) + P(I9) = 5.20E\text{-}02$$

For the hypothetical case which assumes that we are not sure of the crew's transfer to EPP 4, the conditional HEP estimate will be given by ($\mathrm{HEP}_{\mathrm{hypo}}$):

$$P(I2)*P(D1)+ P(I2)*P(D6)+ P(I2)*P(D7)+ P(I9)*P(D1)+ P(I9)*P(D6)+ P(I9)*P(D7)$$

$$= 2.96E\text{-}03$$

HEP estimate using the dependency quantification procedure

As indicated earlier, we are using the hypothetical case, which assumes we are not sure of the crew's transfer to EPP 4, to demonstrate our dependency modeling and quantification methodology. When conditional dependence between the CFMs is assumed, the estimated HEP is given by ($\mathrm{HEP}_{\mathrm{hypodep}}$);

$$P(I2)*P(D1|I2)+ P(I2)*P(D6|I2)+ P(I2)*P(D7|I2)+ P(I9)*P(D1|I9)+ P(19)*P(D6|I9)+ P(I9)*P(D7|I9)$$

$$= 3.17E\text{-}03$$

When compared with HEP_1 (2.96E-03), there is about a 5% increase. Though this increase in HEP is not significantly large (partly due to the nature of model parameter estimates), it still indicates the need to consider dependency between HFE. Irrespective of the numerical values, this demonstrates our dependency modeling and quantification methodology.

15.1.3 Quantitative Analysis using SPAR-H

SPAR-H broadly categories crew failure as either diagnosis failure or action failure and dependency was not accounted for in this analysis. Therefore applying our methodology but using the same assumption like SPAR-H, the relevant CFMs for this HFE will include all the 9 CFMs in I phase (I1 –I9) and the 7 CFMs in the D phase (D1-D7). Since non-dependency quantification is assumed, the estimates of the joint conditional probabilities of these CFMs are given in Table 15-14.

Table 15-14: Joint conditional probability estimates for CFMs in I & D phases

ID	CFMs	Joint conditional failure probability
I1	**Key Alarm not Responded to (intentional & unintentional)**	7.55E-05
I2	**Data Not Obtained (Intentional)**	4.05E-02
I3	**Data Discounted**	4.05E-02
I4	**Decision to Stop Gathering Data**	1.55E-02
I5	**Data Incorrectly Processed**	4.92E-03
I6	**Reading Error**	8.48E-04
I7	**Information Miscommunicated**	3.52E-03
I8	**Wrong Data Source Attended to**	5.88E-04
I9	**Data Not Checked with Appropriate Frequency**	1.17E-02
D1	**Plant/System State Misdiagnosed**	3.95E-02
D2	**Procedure Misinterpreted**	3.75E-03
D3	**Failure to adapt procedures to the situation**	8.94E-03
D4	**Procedure Step Omitted (Intentional)**	6.33E-03
D5	**Inappropriate Transfer to a Different procedure**	6.33E-03
D6	**Decision to Delay Action**	6.33E-03
D7	**Inappropriate Strategy Chosen**	1.11E-02

The conditional HEP estimate is given by (HEP_4):

$$\sum_{i=1}^{16} P(CFM_i)$$

Where i = CFM’s I1 to D7 in Table 15-14.

Therefore HEP_{sparH} = 2.00E-01.

In summary, we have used this ASP example to demonstrate the capabilities of our methodology (both qualitatively and quantitatively).

15.2 CRT Application in Event Assessment

In this example, we will be using the Loss of Inventory Event at Oconee [117] to demonstrate the application of CRT in event assessment during shut down operations. This analysis is considered part of a significant determination process (SDP) because it was done to see the impact of performance deficiency. We have also developed fault trees to link the relevant CFMs to the respective branch points.

Event Summary

"On April 12th, 2008 Oconee Unit 1 shut down for refueling. On April 15th Unit 1 had restored level, from a midloop operation to install cold leg nozzle dams, to below the reactor vessel flange. The head was detensioned in preparation for removal. As part of main generator voltage regulator modification testing, a main generator lockout signal was generated while the switchyard was back-feeding all Unit 1 electrical loads through the main transformer and the associated auxiliary transformer. This caused a slow transfer from the aux transformer to backup transformer (CT1) from the switchyard. The resulting electrical transient caused a momentary loss of power to the running pumps performing shutdown cooling (SDC) and due to one complication, a relief valve in the letdown purification system opened and remained open as designed. This transient caused a loss of inventory (LOI) from the reactor coolant system (RCS) to the miscellaneous waste holdup tank (MWHUT)." [117].

The status of major plant equipment prior to the even was as follows:

- “Reactor in cold shutdown (mode 6) with the reactor head detensioned, but still in place
- RCS level 70 inches above the midloop and approximately 110 inches above top of active fuel (TAF)
- RCS temperature 96 F
- Estimate of time to boil (TTB) of 20 minutes supplied to shift, however, this TTB was calculated for midloop and shift had raised level 70 inches above midloop so TTB would be greater.
- Low pressure injection (LPI) pumps A and B in service supplying decay heat removal and reactor temperature indication
- Low pressure service water (LPSW) loops A and B in service, supporting shut down cooling (SDC)
- All reactor coolant pumps secured
- Low pressure injection (LPI) was cross connected to the high pressure injection (HPI) system for letdown purification
- Steam generator upper primary hand holes removed supplying a large vent for the RCS, cold leg nozzle dams installed” [117]

Crew Action Success Criteria

The crew must recognize the occurrence of an abnormal event and begin the implementation of procedure AP-26 “Loss of Decay Heat Removal”. The specific section that they must start is Section 4C: “RCS Vented and FTC Not Flooded (both primary hand holes removed)”. The crew needs to isolate the leakage before RCS level drops to the middle of the hot leg at which time the low pressure injection (LPI) / shut down cooling (SDC) pumps will begin to cavitate or they need to make up RCS to prevent core damage.

The safety function is to keep RCS's completeness in terms of stopping the leakage or making up RCS. The HFE could be defined in terms of each expected crew action in the process of accomplishing the safety function or a combination of all the crew actions. In terms of a combination of actions, the HFE could be defined as failure of the crew to keep RCS complete. We have constructed a CRT for it, provided the CRT construction questions and answers (Table 15-15), branch point descriptions and applications in the CRT (Table 15-16), and fault trees which link the CFMs (we consider relevant) to some of the branch points in the CRT (Figure 15-11 to Figure 15-22). Note that CFMs have red circles underneath them in the fault trees and the relevant parts of the fault trees are indicated using red lines.

Some key notes about this example

1. In conventional HFE modeling, this event may include four HFEs:
   - The crew isolates the leakage early.
   - The crew makes up RCS early.
   - The crew isolates the leakage late.
   - The crew makes up RCS late.

   These four HFEs may have complicate dependency relations. CRT approach provides more detailed inside knowledge to help address the complicated dependency problem. For example, success sequences S01 & S02 represent the dependency between HFEs the crew isolates the leakage early and the crew makes up RCS early. Two human failure actions in failure sequence F01 (branch points H11 & H12) can be seen as two dependent actions.

2. Note that each branch point is conditional to its preconditions. For example, branch point H11 is conditional to the success paths of branch points D1, F1, and F2. Therefore, the CFMs applied for the failure paths of branch points D1, F1, and F2 should not be applied to the failure path of branch point H11.
3. For branch point D1, the only symptom is the RCS level decreasing and there isn't any passive information (alarm).

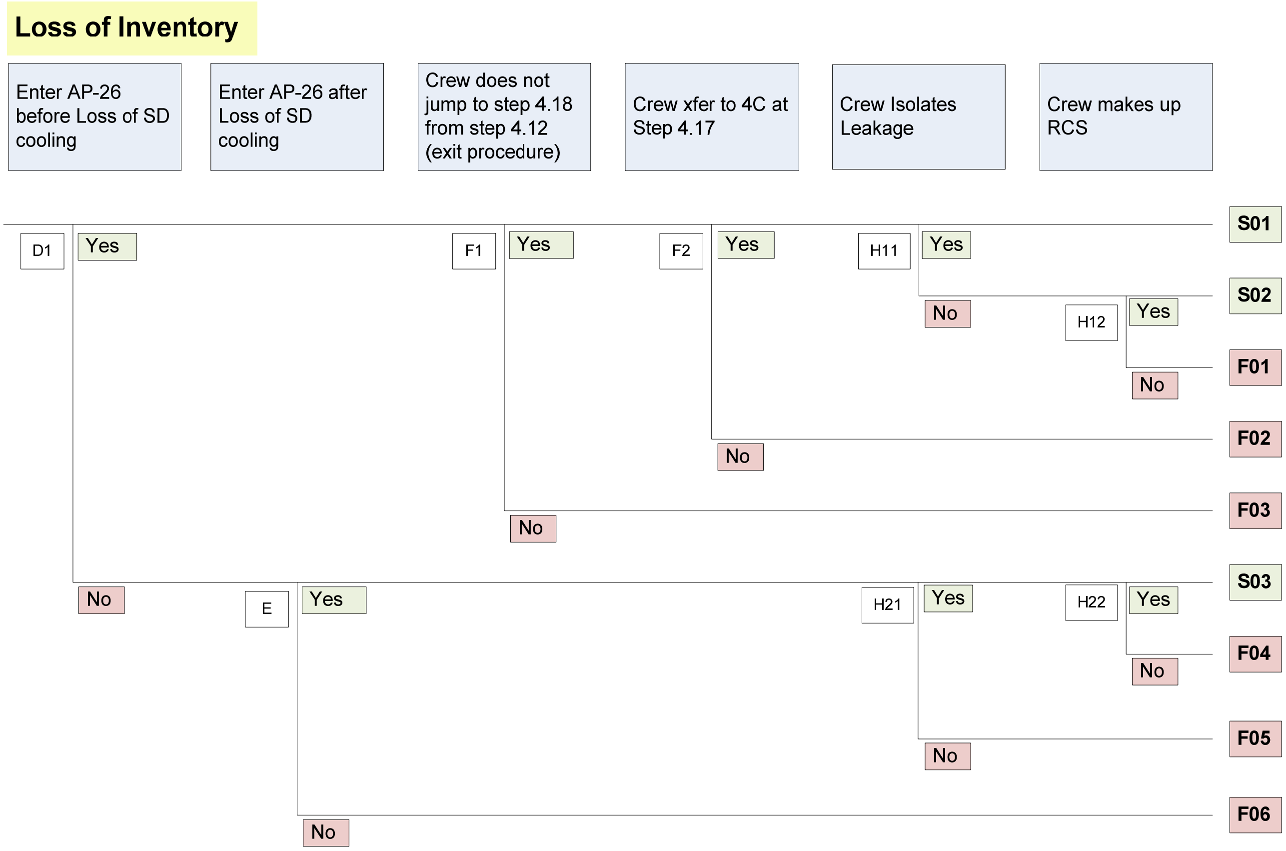


Figure 15-10: CRT for loss of inventory

Table 15-15: Flow chart questions and answers for CRT (restore inventory to RCS)

No.	Question	Answer
1	Is the specific function designed to be initiated automatically?	No, go to Question 3.
2	Is the scenario a fast transient?	NA
3.a	Is there a procedure that includes monitoring and operation of the the specific safety function?	Yes, AP-26. Go to Branch Point D1.
3.b	Is there a specific entry point in the current procedure to a step to manually initiate the safety function?	
4	Are there other procedural entry points that lead to a step to manually initiate the safety function?	Yes, once the RCS level drops to the middle of the hot leg, the LPI/SDC pumps will begin to cavitate and more alarms are shown. Go to Branch Point E.
5.1	Are there any unexplored options under 3.b and 4?	Yes, step 4.12 may lead operators jump to 4.18 and exit this procedure. Go to Branch Point F1.
5.2	Are there any unexplored options under 3.b and 4?	Yes, step 4.17 leads operators transfer to 4C. Go to Branch Point F2.
5.3	Are there any unexplored options under 3.b and 4?	No unexplored points. Go to Branch Point H21.
6.1	Are there additional equipment and manual actions that could be used to provide the specific safety function? This question refers to recovery actions that the crew could potentially take when everything else fails.	Yes, crew may make up the RCS to prevent core damage. Go to BP H12. (Note that to simplify the CRT, Questions 3 & 5, and BPs D & G are all set to yes and they are bypassed).
6.2	Same as 6.1	No. Failure sequence F05
6.3	Same as 6.1	No. Failure sequence F01
6.4	Same as 6.1	No. Failure sequence F04

Table 15-16: Description of success and failure paths for each BP in the CRT

BP	Description	Application in CRT
A	Crew manually initiates the safety function before it is automatically initiated	NA
B	The safety function is automatically initiated	NA
C	Crew does not manually turn off the automatically initiated safety function	NA
D1	This branch point considers (a) whether the crew is in the correct procedure, (b) various options provided by the procedure for success (i.e., multiple choices, each providing a successful path to the critical step to manually initiate the safety function, given the condition)	Branch Point: Crew enters AP-26 • Success Path – Yes, operators enter AP-26 (Go to Question 5.1) • Failure Path – No, operators do not enter AP-26 (Go to Question 4)
E	This branch point considers (c) whether the crew is in the correct procedure, (d) various options provided by the procedure for success (i.e., multiple choices, each providing a successful path to the critical step to manually initiate the safety function, given the condition)	Branch Point: Crew enters AP-26 • Success Path – Yes, crew enters AP-26 (Go to Question 5.3) checked • Failure Path – No, crew does not enter AP-26 (Failed Path F06)
F1	Crew does not transfer to wrong direction from the exit point	Branch Point: Crew does not jump to step 4.18 from step 4.12 • Success Path – Yes, crew does not jump to step 4.12 (Go to Question 5.2) • Failure Path – No, crew jumps to step 4.121. Failure Sequence F03
F2	Crew does not transfer to wrong direction from the exit point	Branch Point: Crew transfers to 4C from step 4.17. • Success Path – Yes, crew transfers to 4C from step 4.17. (Go to BPD11) • Failure Path – No, crew does not transfer to 4C from step 4.171. Failure Sequence F02
H11[2]	Crew successfully initiates the safety function manually	Branch Point: Crew isolates the leakage before loss of shutdown cooling. • Success Path – Yes, crew isolates the leakage before loss of shutdown cooling. Success Sequence S01. • Failure Path – No, crew does not isolate the leakage before loss of shutdown cooling. Go to Question 6.1
H12[2]	Crew successfully initiate the safety function manually	Branch Point: Crew makes up RCS to prevent core damage • Success Path – Yes, crew makes up RCS successfully. Success Sequence S02. • Failure Path – No, crew failed to make up RCS. Go to Question 6.3.
H2	Crew successfully initiates the safety function manually	Because the success criteria here are to isolate the leakage and to make up the RCS, the branch point here is presented as two branch points D21 & D22 in series to represent these two actions.
H21	Crew successfully initiates the safety function manually	Branch Point: Crew isolates the leakage before loss of shutdown cooling. • Success Path – Yes, crew isolates the leakage successfully. Go to BP D22. • Failure Path – No, crew failed to isolate the leakage before loss of shutdown cooling. Go to Question 6.2.
H22	Crew successfully initiates the safety function manually	Branch Point: Crew makes up RCS to prevent core damage. • Success Path – Yes, crew makes up RCS successfully. Success Sequence S03 • Failure Path – No, crew failed to make up RCS. Go to Question 6.4.

[1] Because crew enter AP-26 late with extra alarms, assume that crew will not jump out the AP-26 from step 4.12 & 4.17.

[2] BP G is ignored per the condition that the component was available in this actual event.

Fault Trees

Branch point H11

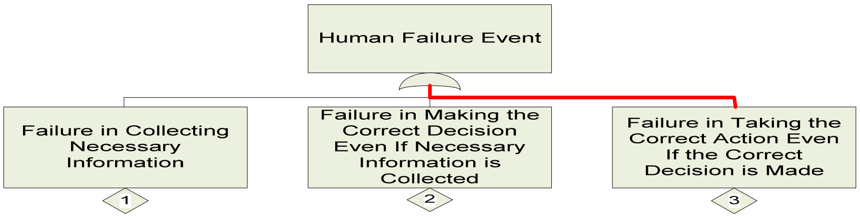


Figure 15-11: HFE logic with phase A as the relevant one for BP H11

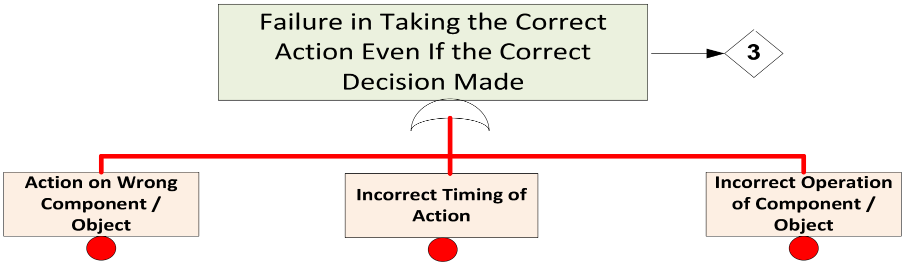


Figure 15-12: A phase part of the fault tree showing the relevant CFMs for BP H11

Branch point H12

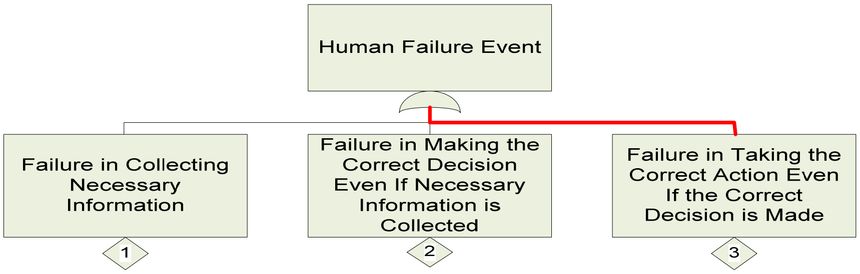


Figure 15-13: HFE logic with phase A as the relevant one for BP H12

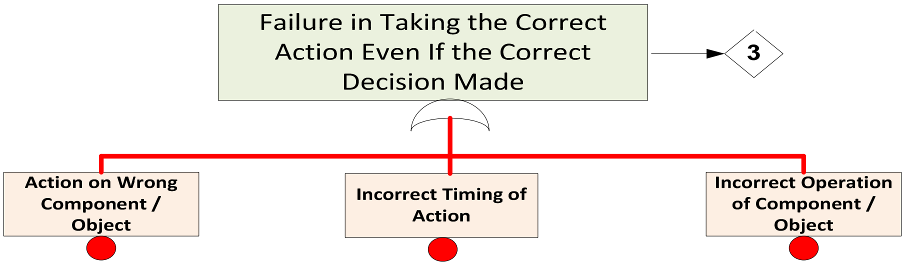


Figure 15-14: A phase part of the fault tree showing the relevant CFMs for BP H12

Branch point D1

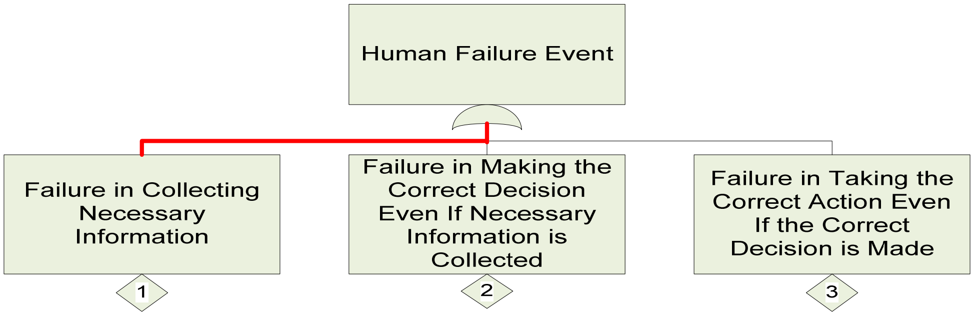


Figure 15-15: HFE logic with phase I as the relevant one for BP D1

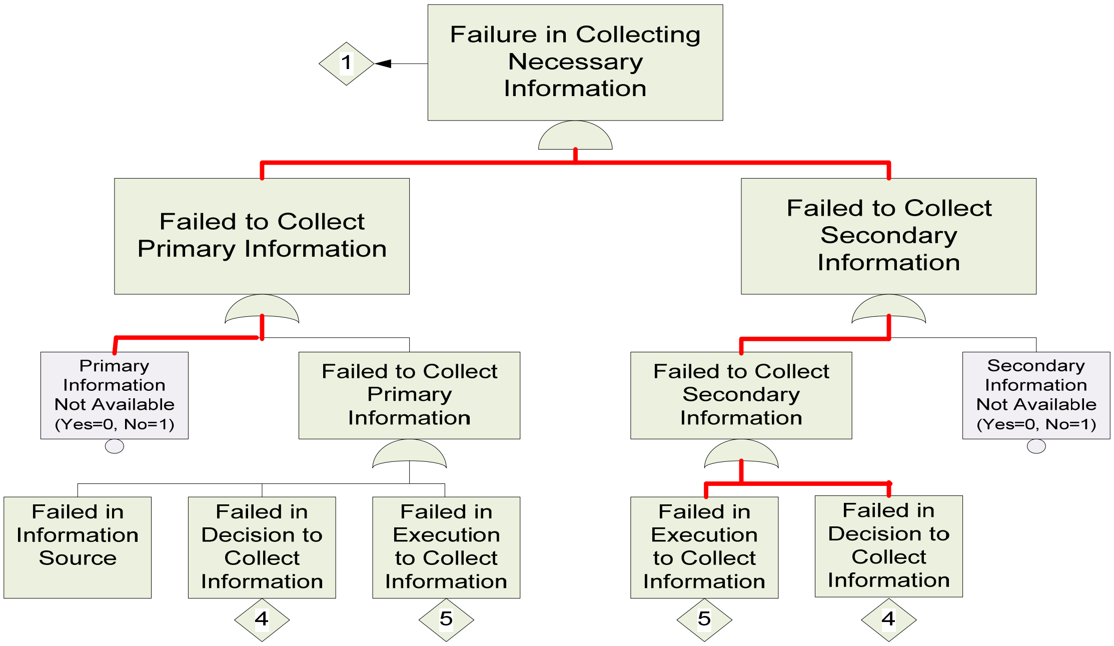


Figure 15-16: Phase 1 part of the FT continued for BP D1

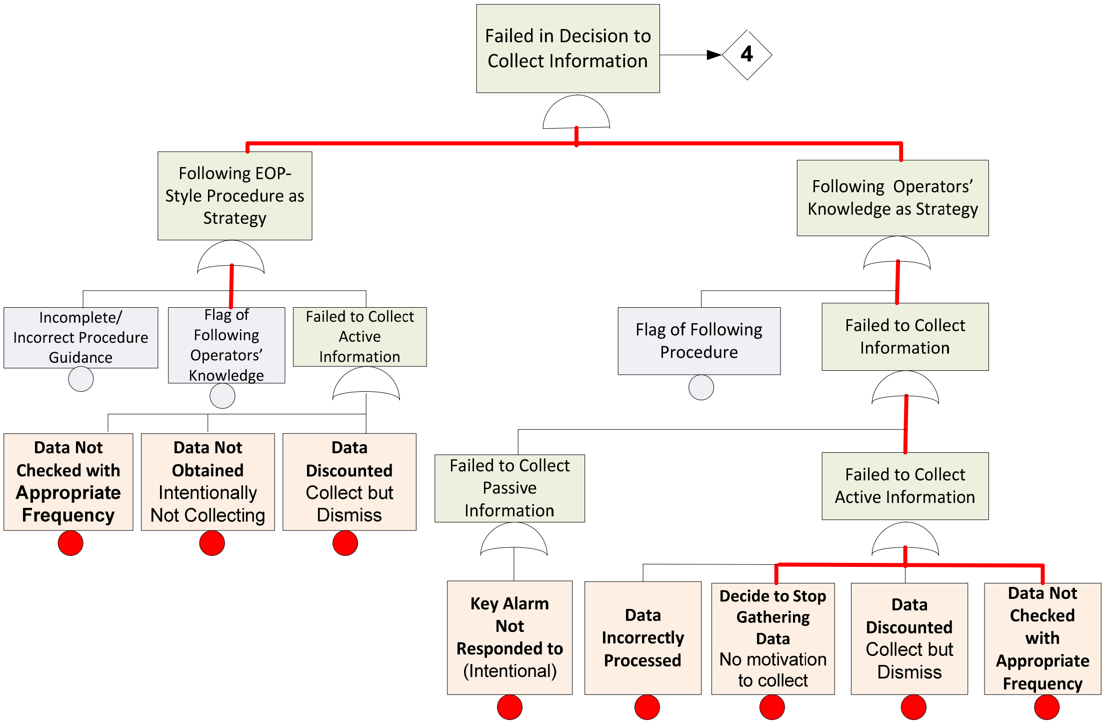


Figure 15-17: Decision in I phase part of the FT showing relevant sections and CFMs for BP D1

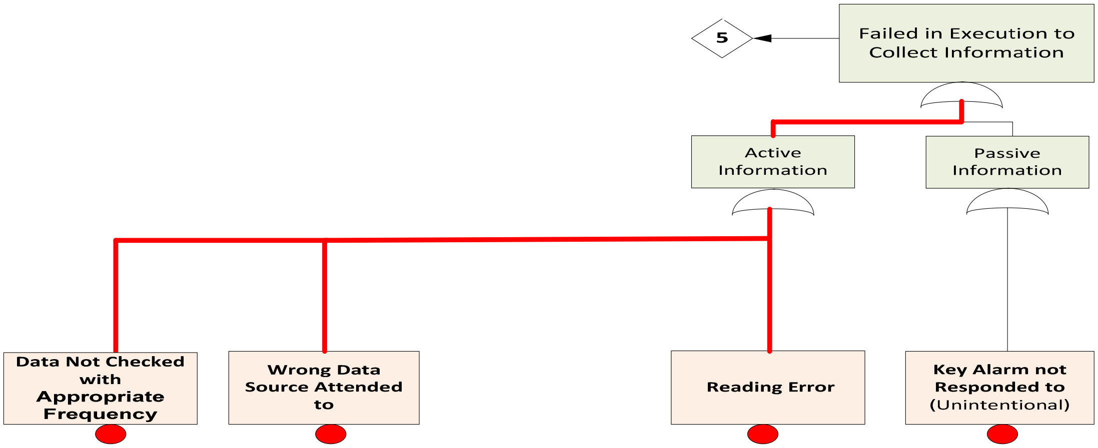


Figure 15-18: Action in I phase part of the FT showing relevant sections and CFMs for BP D1

Branch point E

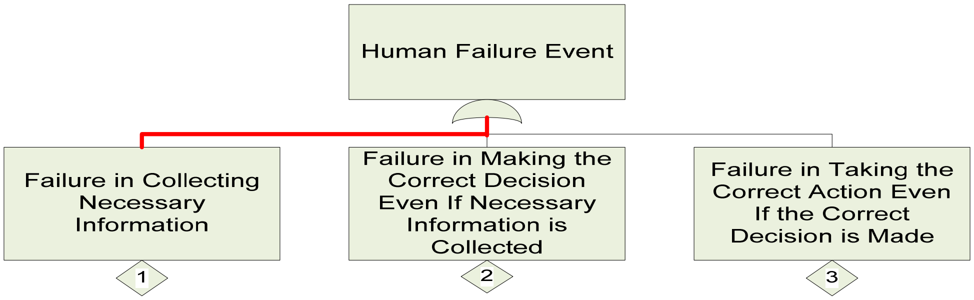


Figure 15-19: HFE logic with phase I as the relevant one for BP E

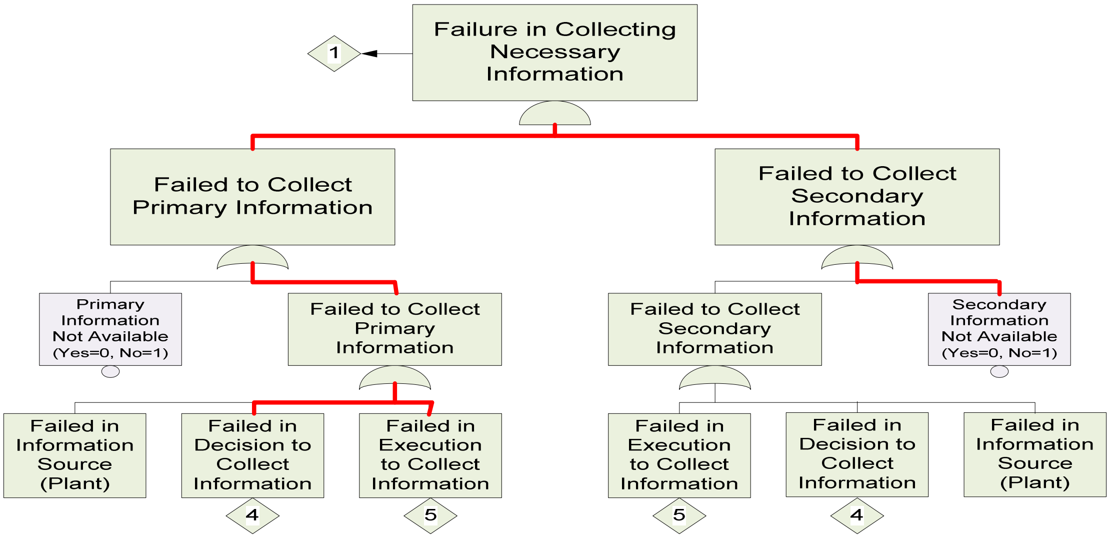


Figure 15-20: Phase 1 part of the FT continued for BP E

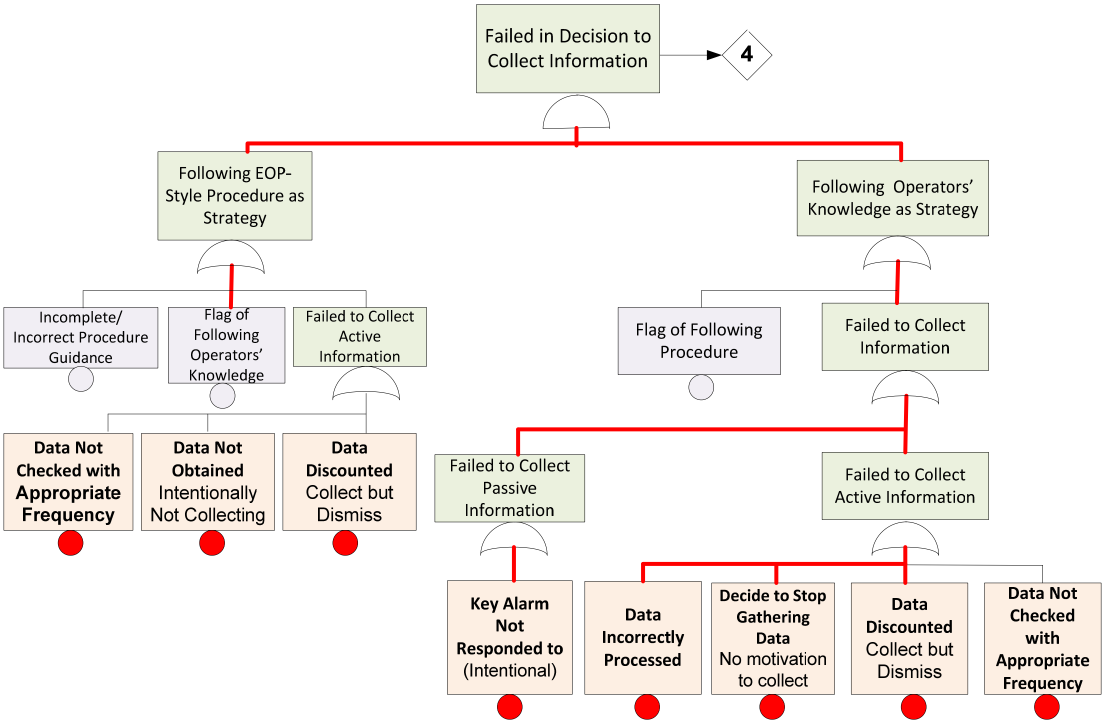


Figure 15-21: Decision in I phase part of the FT showing relevant sections and CFMs for BP E

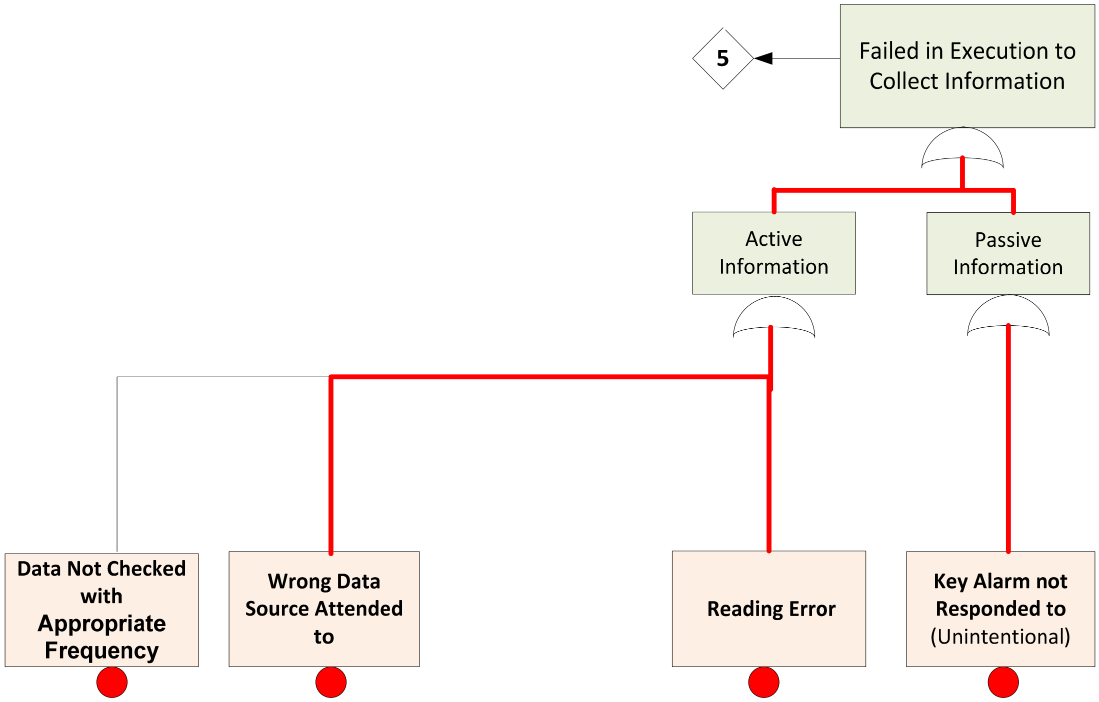


Figure 15-22: Action in I phase part of the FT showing relevant sections and CFMs for BP E

15.3 CRT Application in Heat Sink Control during Loss of Main Feed Initiating Event Example

In this example, we are demonstrating the application of CRT in Heat Sink Control during Loss of main feed initiating event. This is considered at power operations. Once the main feed is lost, the crew needs to initiate the AFW or perform feed & bleed to prevent core damage. In a Westinghouse style EOP, these actions are addressed in EOP FR-H.1. The crew may enter FR-H.1 either from step 14 of EOP E.1 or from the critical safety function tree.

The safety function modeled is to restore heat sink while the HFE could be any of the different combinations of crew failure while carrying out the safety function. We have developed the CRT for this safety function (Figure 15-23) and have used it to demonstrate the modeling of the commission error "the crew turns off the automatically started auxiliary feed water (AFW) when they should not have turned it off" in branch point C. We have provided the CRT construction questions and answers (Table 15-17) and branch point descriptions and applications in the CRT (Table 15-18). Also, we have developed the fault trees (Figure 15-24 and Figure 15-25) linking the relevant CFMs to this branch point as indicated by the red highlighted lines. Note that the fault tree (Figure 15-25) indicates that the crew can jump from following the procedure to relying on their knowledge. The crew started out by following the procedure, but they deviated from it and relied on their knowledge as a strategy, thereby misdiagnosing the plant state.

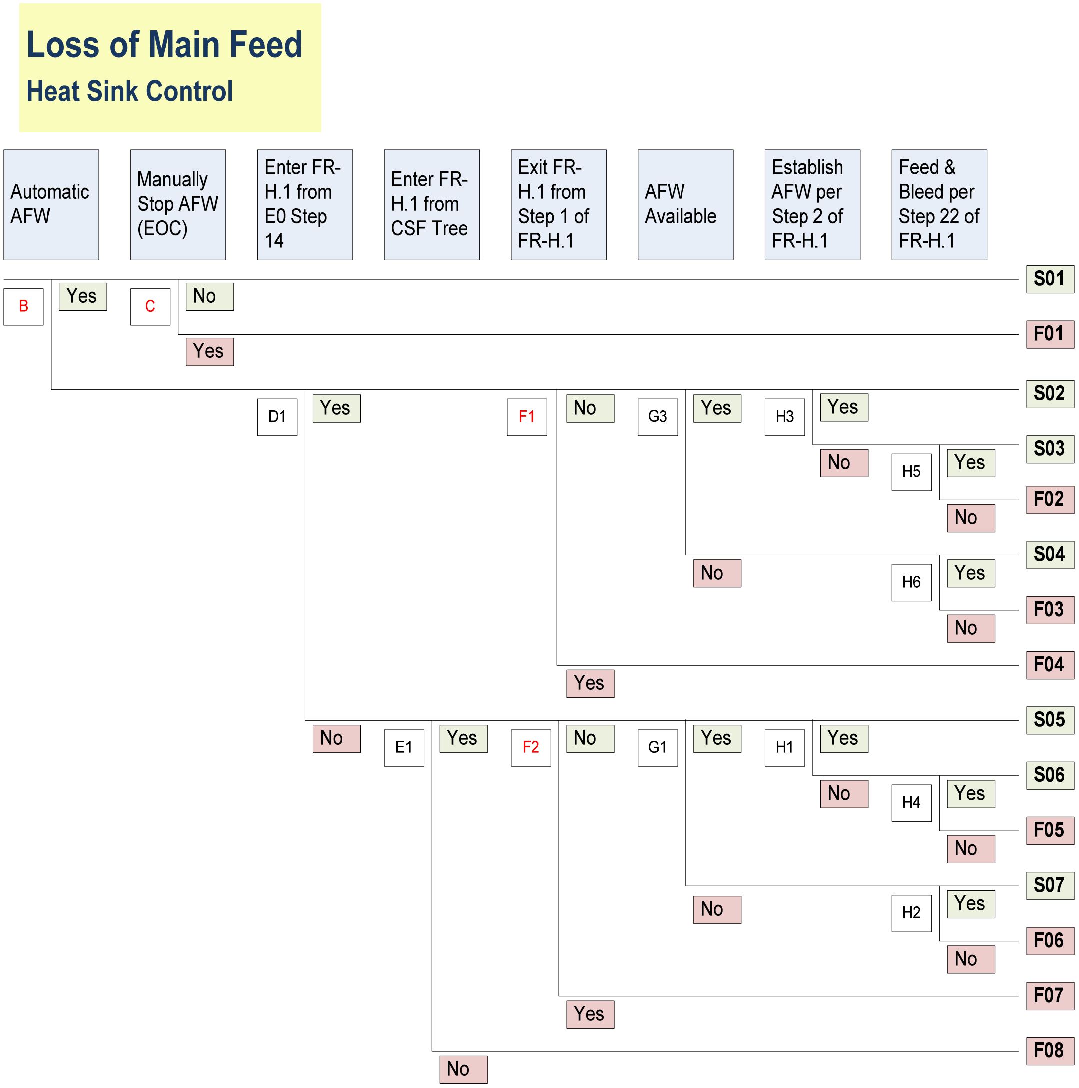


Figure 15-23: CRT for heat sink control during loss of main feed water initiating event

Table 15-17: Flow chart questions and answers - CRT (heat sink control in LMFW)

No.	Question	Answer
1	Is the specific function designed to be initiated automatically?	Yes, AFW is designed to be automatically initiated. Go to Question 2.
2	Is the scenario a fast transient?	Yes, It is a fast transient. Usually, the reactor will be tripped immediately when the main Feed lost. Go to branch point B.
3.a	Is there a procedure that includes monitoring and operation of the the specific safety function?	Yes, procedure FR-H.1 is for this safety function. Crew may enter FR-H.1 from step 14 of E-0. Go to branch point D1.
3.b	Is there a specific entry point in the current procedure to a step to manually initiate the safety function?	
4	Are there other procedural entry points that lead to a step to manually initiate the safety function?	Yes, crew may enter FR-H.1 from red path of critical safety function tree. Go to branch point E1.
5.1	Are there any unexplored options under 3.b and 4?	Yes, crew may exit FR-H.1 when they are performing step 1 of FR-H.1. Go to branch point F1.
5.2	Are there any unexplored options under 3.b and 4?	Yes, crew may exit FR-H.1 when they are performing step 1 of FR-H.1. Go to branch point F2.
6.1	Are there additional equipment and manual actions that could be used to provide the specific safety function? This question refers to recovery actions that the crew could potentially take when everything else fails.	Yes, crew may control the heat sink via Feed and Bleed. Go to branch point H2. (Note that to simplify the CRT, question 3 &5 and BP G in the flow chart guidance are set to be
6.2	Same as 6.1	Yes, crew may control the heat sink via Feed and Bleed. Go to branch point H6. (Note that to simplify the CRT, questions 3 & 5 and BPs D & G in the flow chart guidance are set to be successful, and directly go to BPH)
6.3	Same as 6.1	Yes, crew may control the heat sink via Feed and Bleed. Go to branch point H4. (Note that to simplify the CRT, questions 3 & 5 and BPs D & G in the flow chart guidance are set to be successful, and directly go to BP H)
6.4	Same as 6.1	Yes, crew may control the heat sink via Feed and Bleed. Go to branch point H5. (Note that to simplify the CRT, questions 3 & 5 and BPs D & G in the flow chart guidance are set to be successful, and directly go to BP H)
6.5	Same as 6.1	No. Failure Sequence F06.
6.6	Same as 6.1	No. Failure Sequence F05.
6.7	Same as 6.1	No. Failure Sequence F02.
6.8	Same as 6.1	No. Failure Sequence F03.

Table 15-18: Description of success and failure paths for each BP in the CRT

BP	Description	Application in CRT
A	Crew manually initiates the safety function before it is automatically initiated	NA
B	The safety function is automatically initiated	AFW automatically initiated. Success Path: Yes, AFW automatically initiated. Go to Branch C. Failure Path: No, AFW is not automatically initiated. Go to Question 3.
B	The safety function is automatically initiated	AFW automatically initiated. Success Path: Yes, AFW automatically initiated. Go to Branch C. Failure Path: No, AFW is not automatically initiated. Go to Question 3.
C	Crew does not manually turn off the automatically initiated safety function	Manually stop automatically initiated AFW. Success Path: No, crew does not stop AFW manually – S01.
D1	This branch point considers (e) whether the crew is in the correct procedure, (f) various options provided by the procedure for success (i.e., multiple choices, each providing a successful path to the critical step to manually initiate the safety function, given the condition) So this branch point may produce multiple branches, each of which need to be pursued separately in the CRT. The Success Path corresponds to operator choosing a correct option for the condition and manually initiating the safety function.	Enter FR-H.1 from step 14 of E-0. Success Path: Yes, crew enters FR-H.1 from step 14 of E-0. Go to Question 5.1. Failure Path: No, crew does not enter FR-H.1 from step 14 of E-0. Go to Question 4.
F1	Crew exits FR-H.1 from step 1 of FR-H.1.	Exit FR-H.1 from step 1 of FR-H.1. Success Path: No, crew does not exit FR-H.1 from step 1 of FR-H.1. Go to BP H3. Failure Path: Yes, crew exits FR-H.1. Failure Sequence F04.
F2	Crew exits FR-H.1 from step 1 of FR-H.1.	Exit FR-H.1 from step 1 of FR-H.1. Success Path: No, crew does not exit FR-H.1 from step 1 of FR-H.1. Go to BP H1. Failure Path: Yes, crew exits FR-H.1. Failure Sequence F07.
E1	Similar to Branch Point D, this branch point considers (g) whether the crew is in the correct procedure, (h) various options provided by the procedure for success (i.e., multiple choices, each providing a successful path to the critical step to manually initiate the safety function, given the condition)	Enter FR-H.1 from critical safety function tree. Success Path: Yes, crew enters FR-H.1 from critical safety function tree. Go to Question 5.2 Failure Path: No, crew does not enter FR-H.1. Failure Sequence F08.
G1	Safety function is not impaired by equipment failure	AFW is available. Success Path: Yes, it is available. Go to branch point D1. Failure Path: No, it is not available. Go to Question 6.1. Success Path: Yes, it is available. Go to branch point D1.

H1	Crew successfully initiates the safety function manually	Crew initiates AFW. Success Path: Yes, crew initiates AFW per step 2 of FR-H.1 – Success sequence S05. Failure Path: No, crew failed to initiate AFW. Go to Question 6.3.
H2	Crew successfully initiates the safety function manually	Crew initiates Feed and Bleed. Success Path: Yes, crew initiates Feed and Bleed per step 22 of FR-H.1 – Success sequence S07. Failure Path: No, crew failed to initiate Feed and Bleed. Go to Question 6.5.
G3	Safety function is not impaired by equipment failure	AFW is available. Success Path: Yes, it is available. Go to branch point D3. Failure Path: No, it is not available. Go to Question 6.2.
H3	Crew successfully initiates the safety function manually	Crew initiates AFW. Success Path: Yes, crew initiates AFW per step 2 of FR-H.1 – Success sequence S02. Failure Path: No, crew failed to initiate AFW. Go to Question 6.4.
H4	Crew successfully initiates the safety function manually	Crew initiates Feed and Bleed. Success Path: Yes, crew initiates Feed and Bleed per step 22 of FR-H.1 – Success sequence S06. Failure Path: No, crew failed to initiate Feed and Bleed. Go to Question 6.6.
H5	Crew successfully initiates the safety function manually	Crew initiates Feed and Bleed. Success Path: Yes, crew initiates Feed and Bleed per step 22 of FR-H.1 – Success sequence S03. Failure Path: No, crew failed to initiate Feed and Bleed. Go to Question 6.7.
H6	Crew successfully initiates the safety function manually	Crew initiates Feed and Bleed. Success Path: Yes, crew initiates Feed and Bleed per step 22 of FR-H.1 – Success sequence S04. Failure Path: No, crew failed to initiate Feed and Bleed. Go to Question 6.8.

Fault tree

The fault trees shown here are used to represent the error of commission, “the crew turns off the automatically started auxiliary feed water (AFW) when they should not have turned it off” (branch point C).

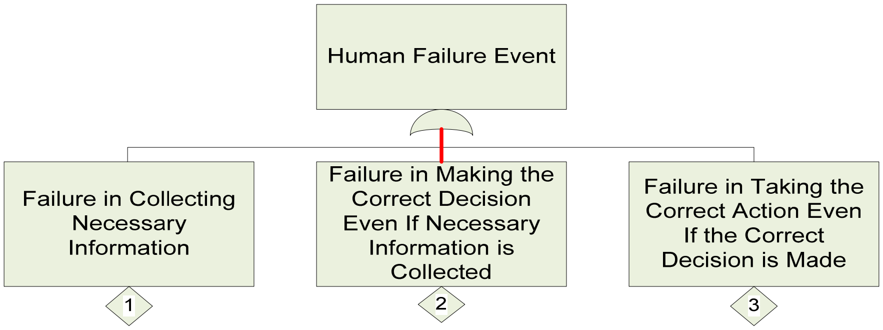


Figure 15-24: HFE logic with phase D as the relevant one for BP C

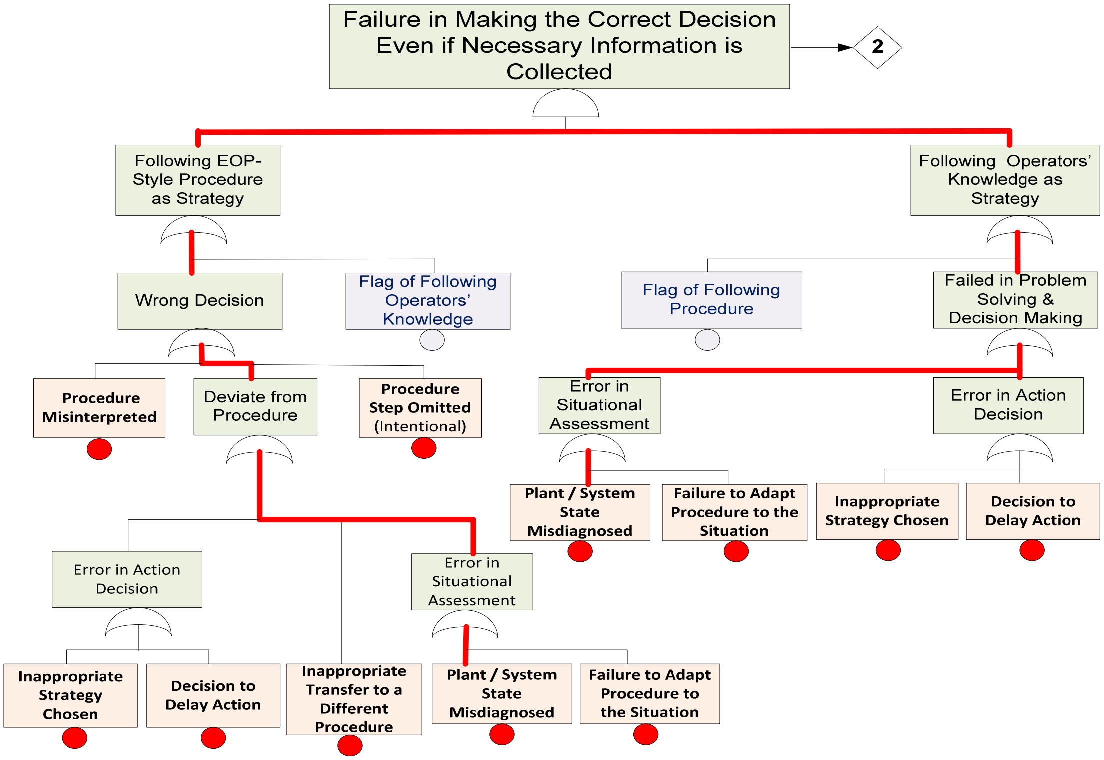


Figure 15-25: D phase of the FT showing the relevant sections and CFMs for BP C

15.4 Example showing the Connection of two CRT Modules

The focus of this example is to demonstrate the connection of two function–level CRTs to form a larger and more comprehensive one. A simplified event tree for the non-recoverable loss of main feed initiating event is provided in Figure 15-26. A CRT (Figure 15-27) is developed for the first top event (RPS) in Figure 15-26. Another one is developed (Figure 15-28) for the second top event (SHSC) in Figure 15-26 as well. The CRT for SHSC is also a continuation of the SHSC end states in the CRT for rector trip (Figure 15-27). Therefore, these two CRTs (RPS and SHSC) are combined together to form a more comprehensive CRT for modeling the first two top events of the event tree for the non-recoverable loss of main feed initiating event.

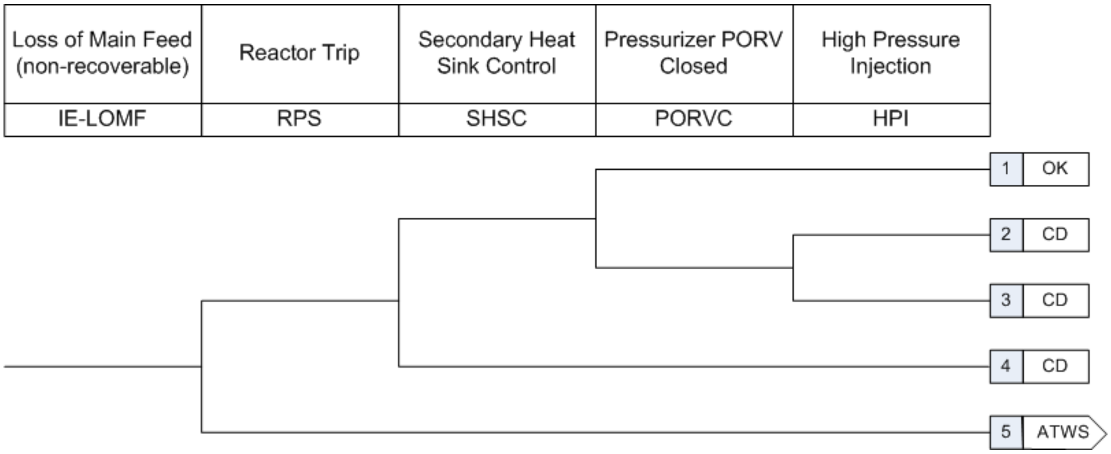


Figure 15-26: Event tree for loss of main feed initiating event

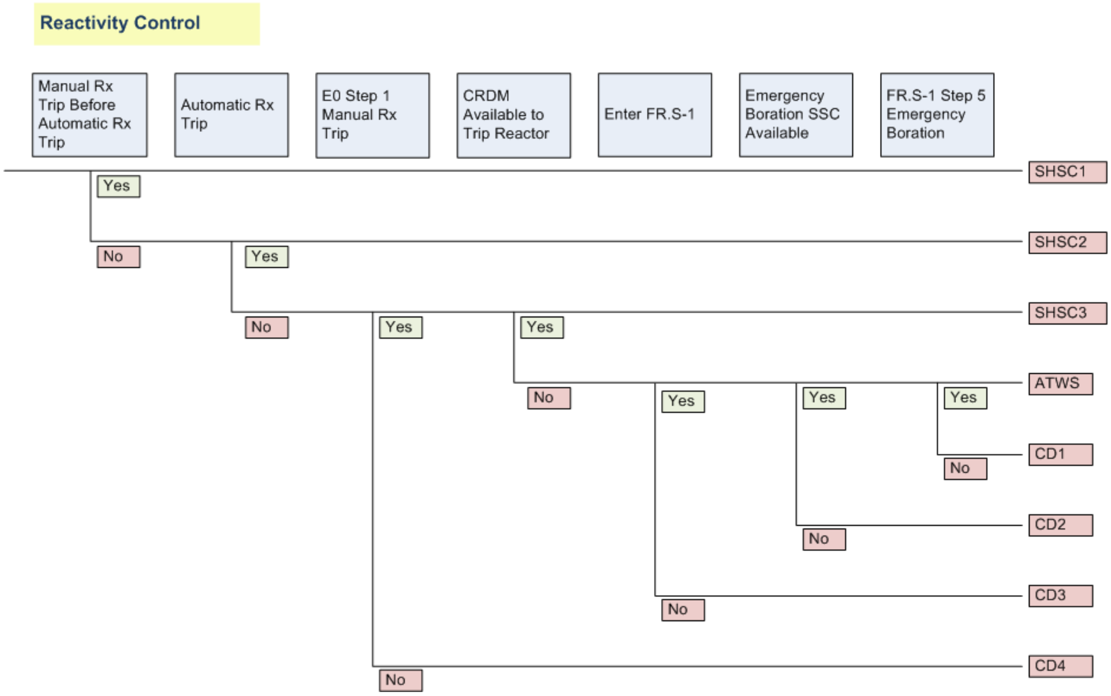


Figure 15-27: CRT representing reactor trip (RPS)

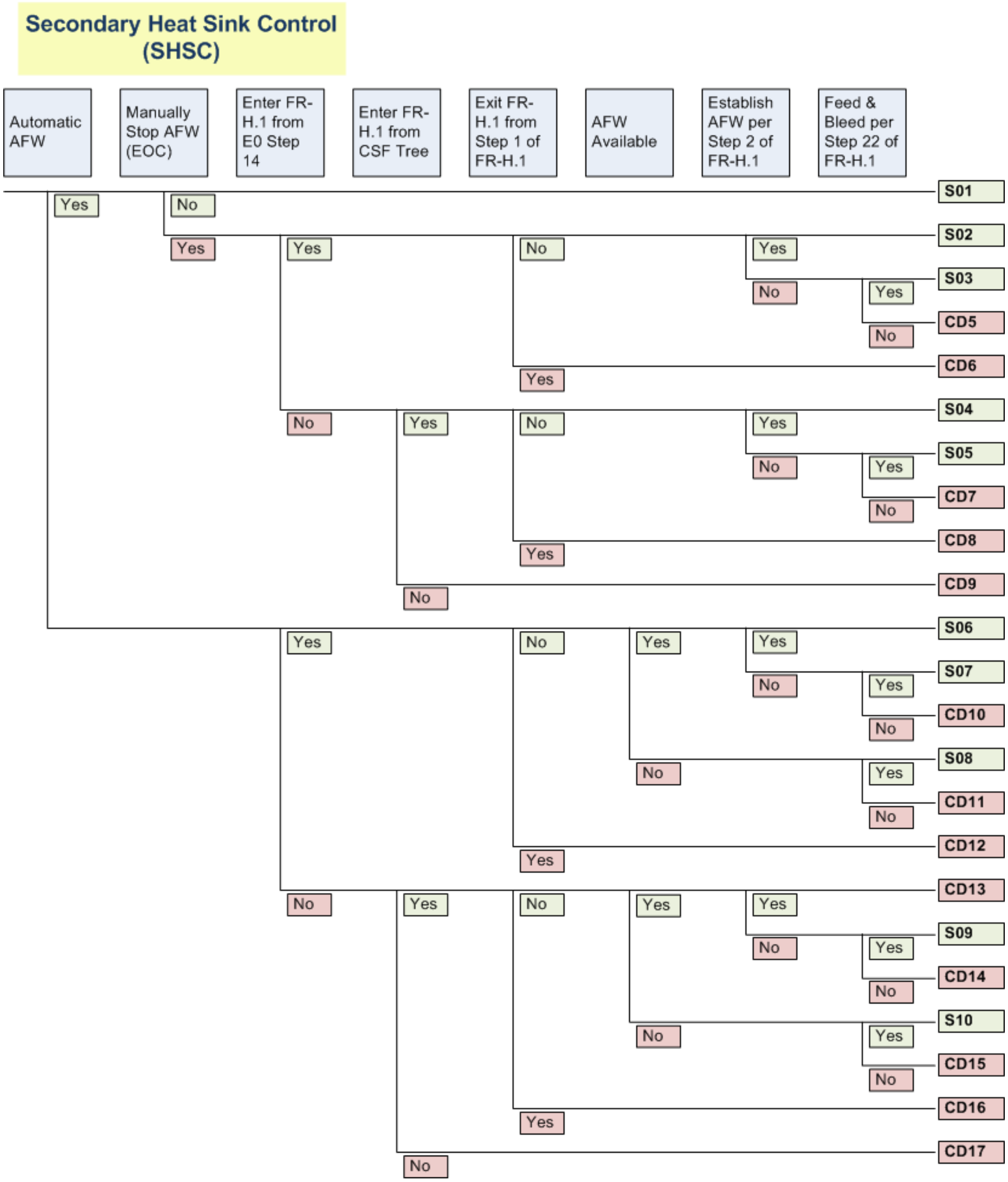


Figure 15-28: CRT representing secondary heat sink control (SHSC)

16 Summary and Conclusion

This dissertation introduces Phoenix HRA, a model-based methodology (both qualitative and quantitative) for conducting HRA. Based on a framework for a model-based HRA that was proposed by Mosleh et al. in [6], [23], this research has developed and enhanced the building blocks, complete methodology and procedure for its implementation. Example applications have been provided to demonstrate the implementation of the entire methodology and some important concepts.

16.1 Foundation of Phoenix HRA

This research is built based on available theories (including cognitive sciences and psychology), experimental results, operating experience (including those of US and German NPPs), and expert opinions (from PRA, & HRA analysts, plant operators, cognitive scientists, psychologists). We have provided two tables, Table 16-1 and Table 16-2, to show the key elements of both the qualitative and quantitative phases of the methodology and the foundation on which they are built on.

Table 16-1: Foundation of the Qualitative Analysis Key Elements

Qualitative Analyis Key Elements	Foundation
Task Analysis	CREAM (cognitive activities and COCOM function)
	PRA context (flexibility and guidance in the level of defining HFEs; functional requirements, and procedures as a basis for defining activities)
	IDAC (decomposition in terms of I, D, A phases and crew response) Task Analysis Theories and Guidelines (e.g., Cognitive Task Decomposition)
CRT	ATHEANA (formalization of ATHEANA "deviation" search method)
	PRA context (events and functions called out in PRA event sequence diagrams and event trees)
	NPP procedures
Human Response Model	IDAC (cognitive model in terms of multi-layered crew response phases I, D, A)
CFMs	SCADA (crew error modes based on operators, PRA and HRA analysts and cognitive science experts)
	IDHEAS (CFMs)
	IDAC (cognitive and action failures modes)
	NPP Operating experience
PIFs	Groth's PIF Taxonomy
	IDAC (PIFs)
	HRA Good Practice (PIFs)
CFM-PIF Framework	Report on Building a Psychological Foundation for HRA (comprehensive literature review and analysis in cognitive sciences, experimental psychology, organizational theories) which includes IDAC model; operating experience from NPP; domain experts including HRA and PRA analysts)
BBN Model structure	CFM - PIF framework
HFE Scenario "cut-set" Identification	HCL Quantitative Algorithm (linked FT, BBN, ESD), IRIS Software

Table 16-2: Foundation of the Quantitative Analysis Key Elements

Quantitative Analysis Key Elements	Foundation
CFM-PIF BBN Model Quantification	Leaky NoisyOR approximation
HFE Dependency Modeling and Quantification	Dynamic Bayesian Network (time slice concept)
	BBN quantification algorithms
Model Parameters	
a) Multipliers	NARA (EPC)
	SPAR-H (Multipliers)
	CREAM (CPCs)
b) Leak Factors	NARA (GTT estimates)
	CREAM (Generic failure type estimates)
	Published expert HEP estimates
	German NPP operating experience
PIF Assessment	Questionnaire Simple Scoring Systems
HFE Scenario Quantification	HCL Quantification Algorithm (linked FT, BBN, ESD), IRIS Software

16.2 Research Contributions

For the qualitative analysis framework (Figure 16-1) which has three layers (CRT, human response model - IDA, PIFs), this research has made the following contributions:

- Proposed guidelines for conducting task analysis in the context of the PRA model, CRT, IDA task decomposition, and crew activities.
- Enhanced the CRT construction process for consistency and completeness by improving the overall structure of the flowchart used for CRT construction and also incorporated timing of crew responses into the CRT.
- Provided a catalog of information required by analyst for conducting HRA.
- Expanded the set of CFMs to capture the various modes in which NPP operating crews fail while conducting their day-to-day activities. The CFMs are used to represent crew failures in terms of the phases of our human response model (IDA).
- Enhanced the human response model (IDA) which is represented using fault trees, for more accurate identification of human failure events (HFEs) and scenarios leading up to the HFEs. This was done by improving its overall structure and expanding it to include all the CFMs proposed for use in this methodology.
- Proposed a set of PIF groups and hierarchy which enables information to be captured at different levels of detail. The PIFs are classified into levels within the groups. Therefore, they form a hierarchical structure which can be fully expanded for use in qualitative analysis and collapsed for use in quantitative analysis. The

main PIF of each group serves as a frontline factor that affects human performance from a causal perspective.

- Proposed a framework for relating CFMs to PIFs based on possible causes of failure and mechanisms for human error. It has been developed based on extensive literature review of psychology, cognitive sciences, operating experience and expert inputs sponsored by the US NRC. This framework provides a means for developing a structured, causal model.
- Developed a BBN causal model based on the CFM-PIF framework to model the effects of the influence of PIFs on crew performance. The BBN model nodes are made up of CFMs and PIFs, and the relationships between the nodes are based on the links in the CFM-PIF framework. This model has the flexibility to be modified for interfacing with existing HRA methods like SPAR-H. Note that this is of particular interest to HRA practitioners since SPAR-H is widely used in US nuclear power plants for HRA.

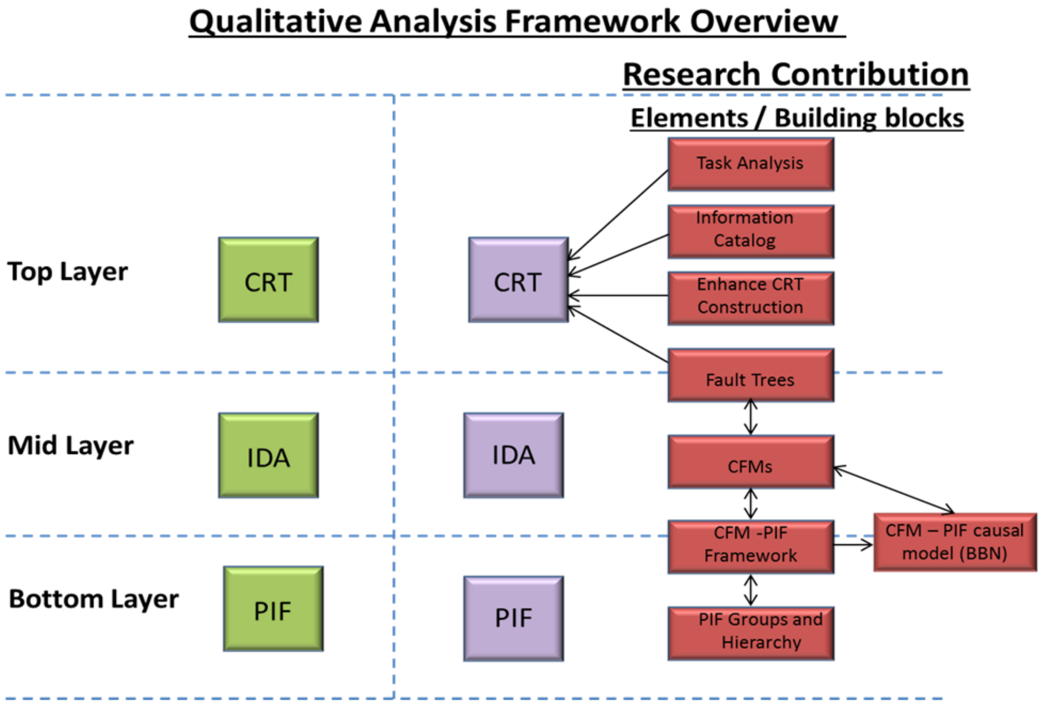


Figure 16-1: Qualitative framework showing the contributions of this research

As part of this research the overall quantification framework (Figure 16-2) and methodology for estimating the HEP has been developed, based on the BBN model. The quantification methodology provides a way to; explicitly treat dependencies between HFEs, account for dynamic effects in terms of changes in the PIF levels during the sequence and ordering of HFEs, incorporate new information and evidence into the HEP estimation process upon availability. Specifically, we have:

- Proposed a methodology for HFE dependency modeling and quantification by incorporating the time slice concept of Dynamic Bayesian Networks (BBN) into BBN modeling and quantification. This is aimed at providing a methodology that can be consistently applied when dealing with dependency between HFEs.

- Proposed a methodology for the BBN model quantification. The use of the BBN model amongst others provides a means to obtain consistent and reproducible HEP estimates.
- Proposed a methodology for assessing the levels of the different PIF states for input into the BBN model. This assessment is done using questionnaires that we have developed. The methodology provides a means of obtaining consistent and reproducible estimates based on the questionnaire. These PIF levels are a part of the model parameters required for HEP estimation.
- Provided estimates of the BBN model parameters by the use of Bayesian methods to incorporate data from sources which included other HRA methods, NPP operating experience, and expert estimates, through a detailed data gathering and analysis process.

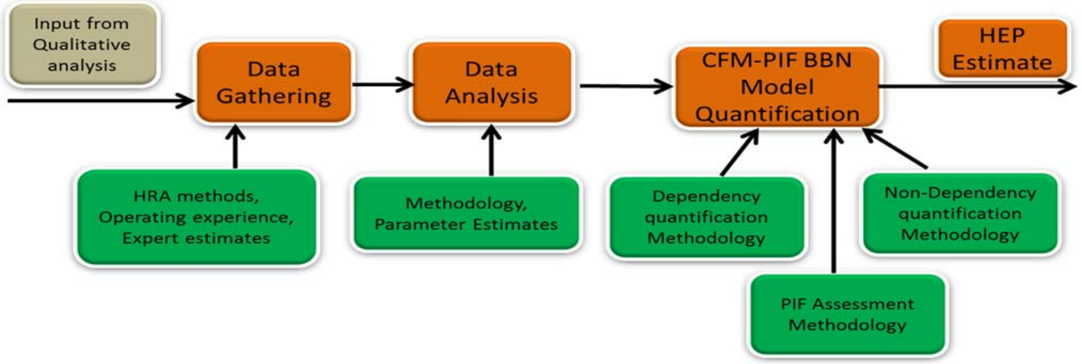


Figure 16-2: Quantification framework showing research contribution

This research is an attempt to develop a comprehensive HRA methodology that encompasses the desirable attributes of a robust HRA method, identified by the team of experts in HRA and related domains [23]. Using these attributes as a set of criteria to evaluate other HRA methods, Table 16-3 gives a summary of how Phoenix HRA has attempted to satisfy them.

Table 16-3: Phoenix HRA and Attributes of a Robust HRA method

No	Attributes of a Robust HRA Method	Phoenix HRA Methodology
1	Content Validity (coverage of plant, crew, cognition, action, errors of commission , errors of omission, etc)	CRT is used to model crew-plant interaction scenarios
		IDA (cognitive) model used to represent human cognition in trems of information processing, decision making, and action execution
		Errors of omission and commission modeled in the CRT and demonstrated usingthe example applications
2	Explanatory power, "causal model" for error mechanisms and relation to context, theoretical foundations	CFM-PIF framework which links CFMs to PIFs based possible causes of failure and mechanisms for human error
		BBN model used to represent the effects of the influence of PIFs on crew performance and for the estimation of HEPs
3	Ability to cover HFE dependency and recovery	Incorporates a methodology that adequately models and quantifies dependency among HFEs
		The ability of the crew to recovery from an error after it is made (global recovery) is incorporated into the CRT construction, while their ability to immediately realize and recover from an error while making it (local recovery) is incorporated in to the conditional probability estimate of that particular failure mode
4	Clear definition of "unit of analysis" and level of detail for various applications	The crew is the unit of analysis and level of detail is determined by applying the task analysis guidelines provided
5	Empirical Validity (of HEPs), e.g., having basis in Operational Data, Simulator Experiments, Other Industries	Model parameter estimation using:
		Data from operating experience (German NPP)
		Data from other HRA methods whose data is generated from a variety of sources which include data bases with roots various indutries such as nuclear,oil & gas, manufacturing, power transmission etc
		Expert generated estimates
		Data from future simulator training (SCADA data base)
6	Reliability (Reproducibly, Consistency, Inter- and Intra-rater Reliability)	The CRT provides a systematic coverage of the crew-plant interactions that is consistent with the scope of the analysis defined in the PRA model. It also supports the documentation and reporting of the analysis
		Task analysis guidleines have been provided to support task decomposition that is consistent with the level of detail required in the analysis
		BBN modeling and quantification provides a means of obtaining consistent and reproducible estimates because the same results are guaranteed given the same set of inputs
		PIF level assessment methodology provides a means of obtaining consistent and reproducible estimates
7	Traceability/Transparency (ability to reverse engineer analysis)	The integrated model (CRT, fault trees and BBN) provides the ability to go from the HFE (modeled in the CRT) to the PIFs modeled in the BBN and vice-versa
8	Testability (of part or the entire model and analysis)	All steps of the analysis (both qualitative and quantitative) proceduralized and provide explicit instructions and mechanisms for recording analyst choices and assumption made
9	Capability for Graded Analysis (screening, scoping, detailed analysis)	Hierarchial task analysis structure which is used for task decomposition to reflect the level of detail required in the analysis
		CRT can be constructed to reflect any level of detail, based on the analyst's definition of the safety function
		Hierarchial structure of PIFs provides the ability to incorporate data into the analysis at the required level of detail
10	Usability/Practicality	Examples given to demonstrate applicability in ASP, SDP, event assessment, power and shut down operations

16.3 Challenges

Aside from the usual challenges one expects to face when working on a research project like this, perhaps the most important challenge was obtaining reliable and relevant information for estimating the BBN model parameters. The BBN model required over 19,000 data points and we had no way of obtaining this information. The data collection problem is a predominant one in HRA and it clearly limits advances in this field.

Hence, we had to apply a modeling technique (Leaky NoisyOR) in order to reduce the required data points to a more reasonable number. We understand that the application of this modeling technique may reduce the types of effects that could be observed from our model. However, we are dealing with a trade-off between producing a very sophisticated model and one that is feasible to quantify.

Even though the Leaky NoisyOR technique drastically reduced the number of data points to about 190, there was still no single data source that could be used to produce these 190 data points. Therefore, we had to map data from different sources, analyze, aggregate, and calibrate based on what is available to us in order to produce estimates for these model parameters.

16.4 Suggestions for Future Work

Even though Phoenix HRA provides an end-to-end methodology for conducting both qualitative and quantitative HRA, there are still some areas that could be further improved.

- Incorporation of data based on operating experience or simulators (e.g., SACADA data base [30] into Phoenix HRA. As discussed in previous chapters, the US NRC is building a data base (SACADA) to support HRA. As part of this research work, we have mapped and established the links of the main elements of the data base to our methodology. We have also provided a means of incorporating it as a data source into our model parameter estimation process, using Bayesian methods. Therefore, when this data base is ready (currently estimated to be available 3 years from now), its output should be used to support both our qualitative and quantitative analysis process.

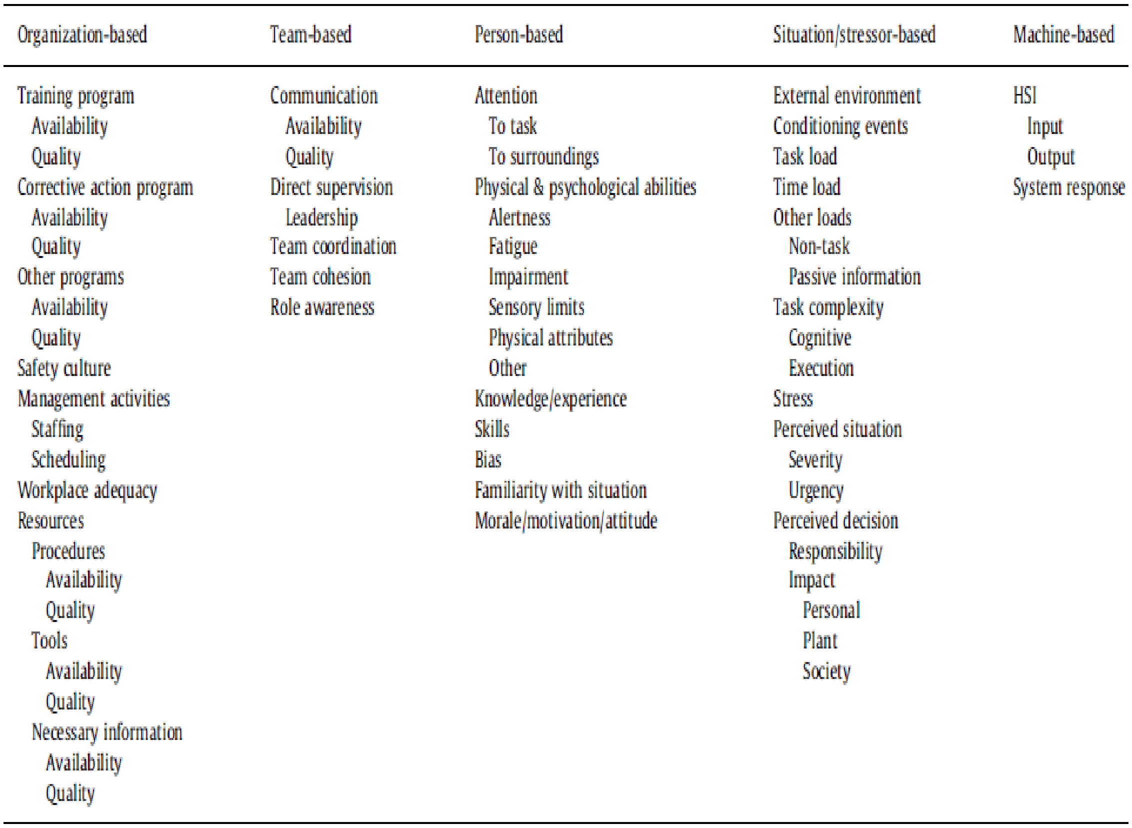
- More work needed on calibration of model parameter estimates. As part of the process of calibrating these estimates, a formal expert elicitation process should be conducted so that the experts can review and provide their inputs.
- PIF assessment questions. These questions should be reviewed by domain experts and extended if necessary.
- Development of a software tool. For practical considerations, automation can hide all the computational and analytical complexity of Phoenix HRA. The analyst view of the software aid can be summarized using a three step process:
    - Analyst answers a series of questions via software user-interface. These questions aim to determine the credible set of specific context factors for the HFE, assess the values of the relevant PIFs that characterize the context, and identify the relevant CFMs. Note that the specific sub-set of questions that an analyst would see in analyzing a particular HFE is determined dynamically depending on the answers to earlier questions, thus reducing the analysis workload. This reflects the fact that situational factors and context characteristics are interdependent.

- Software then generates HEPs and uncertainty distributions based on the analyst's response to questions.
- For multiple HFEs in the same PRA scenario, the analyst answers questions for each HFE in the sequence they appear in the PRA model, and the software will then calculate the corresponding conditional probabilities.

In these steps the analysts only answers questions and is not required to see or modify the BBNs, FTs and probabilistic operations on CRT sequences and corresponding cut-sets.

Appendix A – PIF Sources

Table A1: Tiered PIF classification by Groth [33]



Organization-based	Team-based	Person-based	Situation/stressor-based	Machine-based
Training program	Communication	Attention	External environment	HSI
Availability	Availability	To task	Conditioning events	Input
Quality	Quality	To surroundings	Task load	Output
Corrective action program	Direct supervision	Physical & psychological abilities	Time load	System response
Availability	Leadership	Alertness	Other loads	
Quality	Team coordination	Fatigue	Non-task	
Other programs	Team cohesion	Impairment	Passive information	
Availability	Role awareness	Sensory limits	Task complexity	
Quality		Physical attributes	Cognitive	
Safety culture		Other	Execution	
Management activities		Knowledge/experience	Stress	
Staffing		Skills	Perceived situation	
Scheduling		Bias	Severity	
Workplace adequacy		Familiarity with situation	Urgency	
Resources		Morale/motivation/attitude	Perceived decision	
Procedures			Responsibility	
Availability			Impact	
Quality			Personal	
Tools			Plant	
Availability			Society	
Quality				
Necessary information				
Availability				
Quality				

Table A2: Our PIF set and PIFs from other methods (1/2)

OUR PIFs	Groth's PIF	IDAC PIFs	HRA Good Practice	SPAR-H
HSI Group	HSI	HSI	Ergonomics	Ergonomics / HSI
HSI Input	HSI Input			
HSI Output	HSI Output			
Procedures Group	Procedures		Procedures and Reference Documents	Procedures
Procedure Quality	Procedure Quality	Procedure Adequacy / Quality		
Procedure Availability	Procedure Availability	Procedure Availability		
Resources Group	Resources		Work Processes	Work Processes
Tools	Tools			
Tool Quality	Tool Quality	Tool Adequacy & Quality		
Tool Availability	Tool Availability	Tool Availability		
Work Place Adequacy	Work Place Adequacy	Work Environment (Physical)		
Team Effectiveness Group			processes; Team Dynamics and Characteristics	Work Processes
Communication	Communication			
Communication Quality	Communication Quality	Communication Quality		
Communication Availability	Communication Availability	Communication Availability		
Team Coordination	Team Coordination	Coordination		
Leadership	Leadership	Leadership		
Team Cohesion	Team Cohesion	Cohesiveness		
Role Awareness	Role Awareness	Awareness of Role / Responsibility		
Team Composition	Management activities (staffing)	Composition		
Team Training				
Knowledge / Abilities Group			Fitness for Duty / Fatigue	Experience / Training; Fitness for duty
Knowledge / Experience / Skill (Content)	Knowledge /Experience; Skill	Knowledge /Experience; Skill		
Task Training	Training programs (availability and quality)			
Knowledge / Experience / Skill (Access)	Knowledge /Experience; Skill	Knowledge /Experience; Skill		
Attention	Attention to task; Attention to surroundings	Attention to current task; Attention to surrounding environment		
Physical Abilities and Readiness	Abilities; Alertness; Fatigue; Physical Attributes; Management activities (Scheduling)	Alertness; Fatigue; Physical Abilities		
Bias Group	Bias	Bias	Work Processes	Work Processes
Morale / Motivation / Attitude	Morale / Motivation / Attitude	Morale / Motivation / Attitude		
Safety Culture	Safety Culture	Safety and Quality Culture		
Confidence in Information				
Familiarity with or Recency of Situation	Familiarity with Situation	Perceived Familarity with Situation		
Competing or Conflicting Goals				

Table A2 continued (2/2)

Stress Group	Stress	Stress	Stress and Stressors	Stressors
Stress due to Situation Perception		Perceived Criticality of System Condition		
Perceived Situation Urgency	Perceived Situation Urgency			
Perceived Situation Severity	Perceived Situation Severity	Perceived Severity of Consequence		
Stress due to Decision	Perceived Decision (Responsibility & Impact)	Perceived Decision Responsibility		
Task Load Group	Task load; Time Load	Task-related load; Time Constraint load	Complexity	Complexity
Cognitive Complexity	Task Complexity (Cognitive)	Perceived Task Complexity		
Inherent Cognitive Complexity				
Cognitive Complexity due to external factors				
Execution Complexity	Task Complexity (Execution)	Perceived Task Complexity		
Inherent Execution Complexity				
Execution Complexity due to external factors				
Extra Work Load	Non-task Laod	Non-Task Related Load		
Passive Information Load	Passive Information Load	Passive Information Load		
Time Constraint Group	Time Load	Time -Constraint Load	Available Time	Available Time

Table A3: Mapping of Error Causes from SACADA to our PIFs (1/3)

OUR PIFs	ERROR CAUSES FROM SCADA DATABASE
HSI Group	
HSI Input	
HSI Output	☐ **Label/Mimic/Display Issues**
	☐ **Slight changes**: Slight change is difficult to detect.
	☐ **Unspecific Alarms**: Individual alarms are not specific enough pointing to the system problem.
	☐ **Spurious**: For example, sensor failure triggered the alarm.
	☐ **Failed**: Key alarm failed dark.
	☐ **Misleading Indications**: Subset of indicators gave misleading or conflicting information.
	☐ **Missing Indications**: The primary cue was missing.
	☐ **Distributed**: Relevant information distributed over time/space.
	☐ **Feedback**: Inadequate system feedback, e.g., long system response time
	☐ **Similar Controls**
	☐ **Nonstandard Controls**: Operates differently from standard controls or normal conventions.
Procedures Group	
Procedure Quality	☐ **Procedure-Scenario Mismatch**: Plant conditions do not match procedure assumptions.
	☐ **Conflicting Guidance**: Conflicting guidance in procedures, policies, or practices.
	☐ **Procedure Inadequacy**: Confusable words included in the procedures such as increase and decrease.
Procedure Availability	

Table A3 continued (2/3)

Resources Group	
Tools	
Tool Quality	
Tool Availability	
Work Place Adequacy	
Team Effectiveness Group	
Communication	
Communication Quality	□ **Too Formal**: Overly formal communication substantially delayed/distracted the crew
	□ **Unclear**: Similar sounding words, e.g., increase and decrease.
	□ **Noise**: Noise makes communication difficult.
Communication Availability	□ **High Demand**: Tight communication/coordination demands within MCR.
Team Coordination	▪ **Lack of Familiarity**: Limited experience in working together
Leadership	◊ **Misplaced Trust**: Halo effect (inappropriate assuming that unsupervised work is sufficient).
	◊ **Over Focused**: Too involved in individual tasks
	◊ **Overconfidence**
Team Cohesion	◊ **Non-confrontational**: Disinclined to confront nonconformance.
	▪ **Cohesion Problem**: Baggage or historical issues.
Role Awareness	
Team Composition	▪ **Personnel Shortage**: Shortage of personnel.
	▪ **Experience Mix**: Challenging mix of experience.
	▪ **Personality Mix**: Challenging mix of personality types.
Team Training	
Knowledge / Abilities Group	
Knowledge / Experience / Skill (Content)	▪ **Knowledge Gap**: Lack of knowledge or wrong mental model.
	◊ **Knowledge Gap**: Lack of knowledge or experience/skill
	▪ **Knowledge Gap**: The whole team collectively lacks the required knowledge
Task Training	□ **Alarm Unexpected**: Alarms are triggered by more than one plant malfunctions. The alarms triggered by one of the malfunctions were either not detected or omitted.
	□ **Unfamiliar/Unrecognizable Alarm Pattern**: Alarm did not show recognizable pattern in pointing to the system problem.
	□ **Unfamiliar**: unfamiliar scenario.
Knowledge / Experience / Skill (Access)	▪ **STAR**: Fail to stop, think, act, and review.
	▪ **No Obvious Causes**: e.g., mental lapse and loss of focus.
Attention	▪ **Multiple Demands**: Multiple competing demands on attention.
	▪ **Attention Distracted.**
Physical Abilities and Readiness	▪ **Slow**: slow in thinking, moving, monitoring, and communication.
Bias Group	
Morale / Motivation / Attitude	▪ **Lack of Questioning Attitude**: Lack of discussion of concern.
	◊ **Disrespect: Disrespect of others**
Safety Culture	
Confidence in Information	□ **Motivation**: No reason to check.
	□ **Ambiguous/Unreliable**: Ambiguous/subtle cues.
Familiarity with or Recency of Situation	▪ **Habit Intrusion**: Highly practiced response interfered with desired response.
	□ **Pre-disposed (Fake-out)**: Initial symptoms capture thinking leading to misdiagnosis.
	□ **Mismatch**: Plant response mismatch prior training/experience.
	□ **Prior Experience**: Plant responses mismatched with prior training or experience.
Competing or Conflicting Goals	□ **Competing priorities**: Multiple competing goals.

Table A3 continued (3/3)

Stress Group	▪ **Stressors**: Psychological/physical stressors.
Stress due to Situation Perception	
Perceived Situation Urgency	
Perceived Situation Severity	
Stress due to Decision	
Task Load Group	□ **Complex**: Complex system dynamics.
Cognitive Complexity	▪ **Memory**: Demand on memory.
Inherent Cognitive Complexity	
Cognitive Complexity External to the Mind	□ **Masked**: Masked cue.
Execution Complexity	▪ **Tempo**: High temp tasks.
Inherent Execution Complexity	
Execution Complexity External to the Mind	
Extra Work Load	
Passive Information Load	o **Multiple Alarms**: Multiple simultaneous alarms causing distraction on individual alarm detection or pattern recognition
Time Constraint Group	▪ **Rushing**: Responding to real or perceived time pressure.

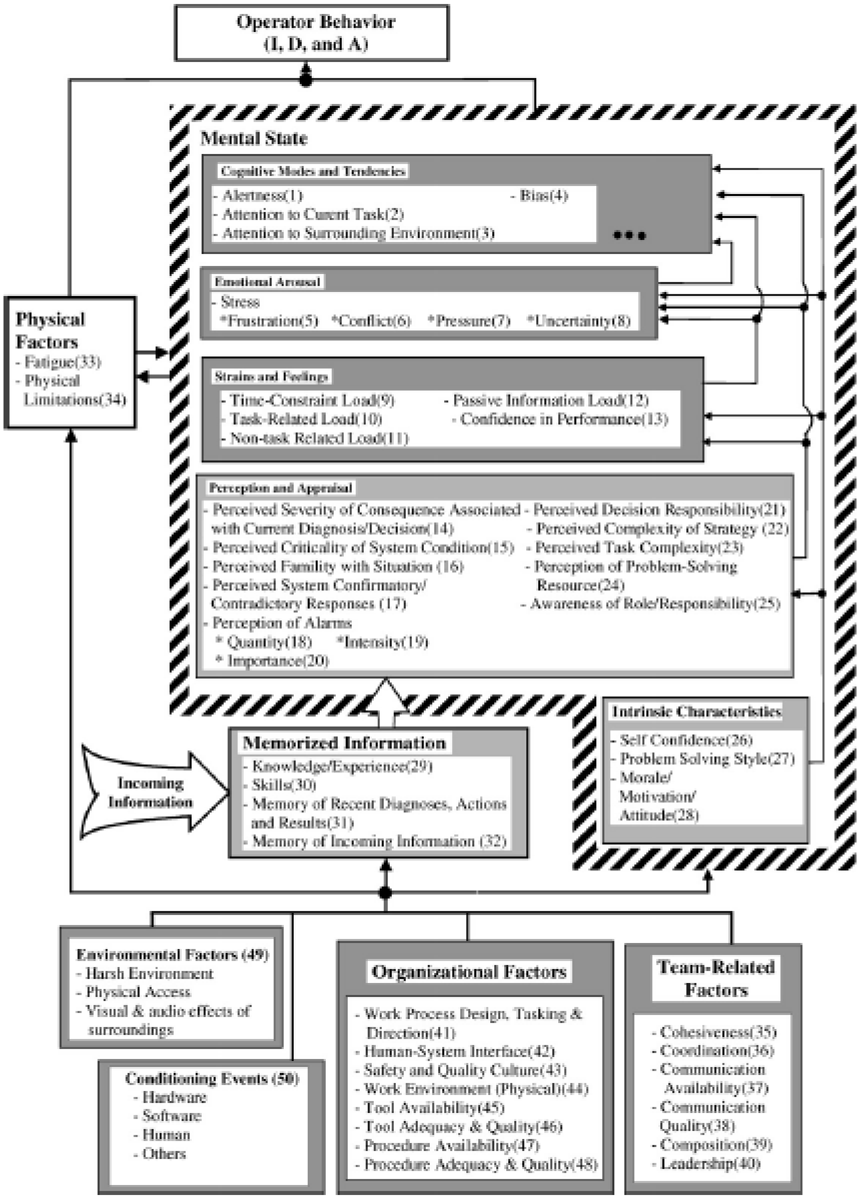


Figure A1: IDAC PIF Hierarchical Structure

Appendix B – CFM-PIF Framework

Phase of Crew Interaction with Plant	Crew Failure Mode	Macro-Cognitive Function	Proximate Cause	Cognitive Failure Mechanism	PIFs
Information phase	Key Alarm not Responded to (Intentional and Unintentional)	Detection	Cues/information not perceived	Attention - Missing a change in cues	Morale/motivation/attitude
					HSI output
					HSI input
					Attention
				Vigilance and monitoring - unable to maintain vigilance	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					HSI
					Task load
					Extra work load
					Stress
					Attention
					Cognitive complexity
					Execution complexity
					Familiarity with or recency of situation
					Morale/motivation/attitude
					Physical abilities and readiness
					Bias
					Time constraint
				Cue content - cue quality is low and not detected	HSI
					Task load
					Time constraint
					Cognitive complexity
					Execution complexity
					Stress
				Working memory - working memory capacity overflow	HSI
					Task load
			Cue/information not attended to	Attention - Missing a change in cues	HSI
					Task load
					Cognitive complexity
					Execution complexity Stress
					Physical abilities and readiness
				Vigilance and monitoring: divided attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					HSI
					Task load
					Physical abilities and readiness
					Stress
					Attention
					Cognitive complexity
					Execution complexity

					Familiarity with or recency of situation
					Morale/motivation/attitude
					Bias
				Cue content - too many meaningful cues	HSI
					Task load
					Cognitive complexity
					Execution complexity
					Stress
					Physical abilities and readiness
				Working memory: working memory capacity overflow	HSI
					Task load
			Cue/information misperceived	Vigilance and monitoring: divided attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					HSI
					Task load
					Physical abilities and readiness
					Stress
					Attention
					Cognitive complexity
					Execution complexity
					Familiarity with or recency of situation
					Morale/motivation/attitude
					Bias
				Cue content - cues too complex	HSI
					Task load
					Cognitive complexity
					Execution complexity
					Stress
					Physical abilities and readiness
					Team coordination
					Attention
		Decision	Incorrect goals or priorities	Goal conflict	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					HSI output
					Stress due to decision
					Safety culture
				Incorrect prioritization of goals	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Resources
					Procedures

					Task load
					Safety culture
		Action	Failure to execute desired action (EOO)	Divided attention	Task load
					Extra work load
					Work place adequacy
					Time constraint
			Execute desired action incorrectly	Dual task interference	HSI
					task load
					Extra work load
					competing or conflicting goals
					Time constraint
				Task switching interference	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					task load
					Extra work load
					Time constraint
				Population stereotypes	HSI
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress
					Team training
					Task Training
				Motor learning	Team training
					Task Training
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
				Recognition errors	HSI
	Data not Obtained (Intentional)	Understanding	Incorrect integration of information frames, or information with a frame/mental model	Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Improper aspects of the data selected for comparison with/identification of a frame	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Procedures
				Improper aspects of the frame selected for comparison with the data	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Incorrect or failure to match data/ information to a frame/mental model	HSI output
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Team training

					Task Training
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Task load
					Time constraint
					Procedures
			Incorrect frame	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Morale/motivation/attitude
					Procedures
				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Frame/mental model inappropriately rejected/ reframed when it should be preserved/ confirmed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
				No frame/mental model exists to interpret the information/situation	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Cognitive complexity
					Execution complexity
					HSI output
					Procedures
		Decision	Incorrect goals or priorities	Incorrect goals selected	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output

					Procedures
					Task load
					Time constraint
				Goal conflict	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					HSI output
					Stress due to decision
					Safety culture
				Incorrect prioritization of goals	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Resources
					Procedures
					Task load
					Safety culture
				Incorrect judgment of goal success	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					Task load
					Time constraint
					HSI
			Incorrect mental simulation or evaluation of options	Inaccurate portrayal of action	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Cognitive complexity
					Task load
					Time constraint
				Incorrect inclusion of alternatives	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Task load
					Time constraint
				Misinterpretation of procedures	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					HSI output

					Task load
					Time constraint
				Inaccurate portrayal of the system response to the proposed action	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					Task load
					Time constraint
				Cognitive bias	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Task load
					Time constraint
	Data Discounted	Understanding	Incorrect integration of information, frames or information with a frame/mental model	Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Improper aspects of the frame selected for comparison with the data	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Incorrect or failure to match data/ information to a frame/mental model	HSI output
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Team training
					Task Training
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Task load
					Time constraint
					Procedures
				Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
			Incorrect/ incomplete/ improper frame/mental	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)

			model used to understand the situation		Team training
					Task Training
					Morale/motivation/attitude
					Procedures
				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
		Decision	Incorrect goals or priorities	Incorrect goals selected	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Procedures
					Task load
					Time constraint
				Goal conflict	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					HSI output
					Stress due to decision
					Safety culture
				Incorrect prioritization of goals	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Resources
					Procedures
					Task load
					Safety culture
				Incorrect judgment of goal success	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					Task load
					Time constraint
					HSI

			Incorrect internal pattern matching	Not updating the mental model to reflect the changing state of the system	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
				Cognitive biases	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Task load
					Time constraint
	Decision to Stop Gathering Data	Understanding	Incorrect/ incomplete/ inaccurate information used to understand the situation	Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
				Improper data/aspects of the data selected for comparison with/identification of a frame	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Procedures
			Incorrect integration of information, frames or information with a frame/mental model	Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
				Improper aspects of the data selected for comparison with/identification of a frame	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Procedures
				Improper aspects of the frame selected for comparison with the data	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Incorrect or failure to match data/ information to a frame/mental model	HSI output
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures

					Team training
					Task Training
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Task load
					Time constraint
					Procedure quality
				Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
			Incorrect/ incomplete/ improper frame/mental model used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Morale/motivation/attitude
					Procedures
				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
		Decision	Incorrect goals or priorities	Incorrect goals selected	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Procedures
					Task load
					Time constraint
				Goal conflict	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					HSI output

					Stress due to decision
					Safety culture
				Incorrect prioritization of goals	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Resources
					Procedures
					Task load
					Safety culture
				Incorrect judgment of goal success	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					Time constraint
					Task load
					HSI
			Incorrect internal pattern matching	Not updating the mental model to reflect the changing state of the system	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
				Cognitive biases	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Time constraint
					Task load
			Incorrect mental simulation or evaluation of options	Inaccurate portrayal of the system response to the proposed action	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
					Time constraint
					Task load
				Cognitive biases	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Time constraint
					Task load
	Data Incorrectly Processed	Understanding	Incorrect integration of information, frames or information with	Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)

			a frame/mental model		Procedures
				Improper aspects of the data selected for comparison with/identification of a frame	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Procedures
				Improper aspects of the frame selected for comparison with the data	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Incorrect or failure to match data/ information to a frame/mental model	HSI output
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Team training
					Task Training
				Improper control of attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					HSI output
					Stress
					Task load
					Time constraint
					Team training
					Task Training
					Work place adequacy
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
					Task load
					Time constraint
					Procedures
				Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
			Incorrect frame used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Morale/motivation/attitude
					Procedures

				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
				No frame/mental model exists to interpret the information/situation	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Cognitive complexity
					Execution complexity
					HSI output
					Procedures
		Decision	Incorrect internal pattern matching	Not updating the mental model to reflect the changing state of the system	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Procedures
				Failure to retrieve previous experiences	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI output
				Incorrect recall of previous experience	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Time constraint
					Task load
				Incorrectly comparing the mental model to previously encountered situations	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Cognitive complexity
					Execution complexity
					Attention
					Time constraint
					Task load
				Cognitive biases	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)

					Team training
					Task Training
					Time constraint
					Task load
			Incorrect mental simulation or evaluation of options	Incorrect inclusion of alternatives	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Time constraint
					Task load
				Cognitive biases	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					Time constraint
					Task load
	Reading Error	Detection	Cues / info misperceived	Attention - Missing a change in cues	HSI
				Vigilance and monitoring: divided attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					HSI
					Task load
					Physical abilities and readiness
					Stress
					Attention
					Cognitive complexity
					Execution complexity
					Familiarity with or recency of situation
					Morale/motivation/attitude
					Bias
				Cue content: cues too complex	HSI
					Task load
					Cognitive complexity
					Execution complexity
					Stress
					Physical abilities and readiness
					Team coordination
					Attention
				Expectations: mismatch between expected and actual cues	Cognitive complexity due to external factors
					Execution complexity due to external factors
					Task load
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Attention

					Familiarity with or recency of situation
					Morale/motivation/attitude
					Physical abilities and readiness
					Bias
				Working memory - working memory capacity overflow	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI
					Task load
		Understanding	Incorrect integration of information, frames or information with a frame/mental model	Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training
					HSI Output
					Procedure quality
				Improper control of attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress
					Task load
					Time constraint
					Team training
					Task Training
					Work place adequacy
					HSI output
		Action	Execute desired action incorrectly	Dual task interference	HSI
					task load
					Extra work load
					competing or conflicting goals
					Time constraint
				Task switching interference	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Task load
					Extra work load
					Time constraint
				Negative transfer / habit intrusion	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Task load
					Team training
					Task Training
				Recognition errors	HSI
	Information Miscommunicated	Crew Coordination	Failure of team communication	Source of error of omission	Time constraint
					Task load
					Resources

					Leadership
					Team cohesion
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress due to situation perception
					Role awareness
					Physical abilities and readiness
					Team training
					Task Training
					communication
					confidence in the information
					Familiarity with or recency of situation
				Source of error of commission	Time constraint
					Task load
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Cognitive complexity
					Execution complexity
					Leadership
					Resources
					Morale/motivation/attitude
					Procedures
					HSI output
					Confidence in information
				Target error of omission	Cognitive complexity due to external factors
					Execution complexity due to external factors
					Task load
					Morale/motivation/attitude
					HSI output
					HSI
					Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Tool quality
					Stress
					Cognitive complexity
					Execution complexity
					Familiarity with or recency of situation
					Morale / motivation / attitude
					Physical abilities and readiness

					Bias
					Time constraint
					Team coordination
					Procedure quality
					Procedures
					Stress
					Confidence in information
				Target error of commission	Team training
					Task training
					Procedures
					Role awareness
					Cognitive complexity due to external factors
					Execution complexity due to external factors
					Task load
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					HSI output
					Procedure quality
					Attention
					Time constraint
					Stress
					Cognitive complexity
					Execution complexity
				Incorrect timing of communication	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Time constraint
					Task load
	Wrong Data Source Attended to	Understanding	Incorrect/ incomplete/ inaccurate information used to understand the situation	Attention to wrong/inappropriate information	HSI output
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
				Improper data/aspects of the data selected for comparison with/identification of a frame	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedures
			Incorrect integration of information, frames or information with a frame/mental model	Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task Training

					HSI Output
					Procedure quality
				Improper control of attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress
					Task load
					Time constraint
					Team training
					Task Training
					Work place adequacy
					HSI output
			Incorrect frame used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Morale/motivation/attitude
					Procedures
				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
		Action	Execute desired action incorrectly	Task switching interference	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					task load
					Extra work load
					Time constraint
				Negative transfer / habit intrusion	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					task load
					Team training
					Task training
	Data Not Checked with Appropriate Frequency	Understanding	Incorrect/ incomplete/ inaccurate information used to understand the situation	Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
			Incorrect integration of data, frames, or data with a frame	Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)

					Procedures
				Improper aspects of the frame selected for comparison with the data	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Task load
					Time constraint
					Procedures
				Improper control of attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress
					Task load
					Time constraint
					Team training
					Task training
					Work place adequacy
					HSI output
				Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
			Incorrect/incomplete/improper frame used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Morale/motivation/attitude
					Procedures
				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
		Action	Execute desired action incorrectly	Task switching interference	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)

					task load
					Extra work load
					Time constraint
				Negative transfer / habit intrusion	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					task load
					Team training
					Task training
		Decision	Incorrect internal pattern matching	Not updating the mental model to reflect the changing state of the system	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
Decision Phase	Plant/System State Misdiagnosed	Understanding	Incorrect data used to understand the situation	Information available in the environment is not complete, correct, accurate, or otherwise sufficient to create understanding of the situation	HSI output
					Cognitive complexity
					Execution complexity
					Procedure quality
					Procedure availability
				Attention to wrong/inappropriate information	HSI output
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
				Improper data/aspects of the data selected for comparison with/identification of a frame	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedures
				Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedure quality
			Incorrect integration of data, frames, or data with a frame	Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedure quality
				Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)

					Knowledge / experience /skill (access)
					Procedures
				Improper aspects of the data selected for comparison with/identification of a frame	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedures
				Improper aspects of the frame selected for comparison with the data	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Incorrect or failure to match data/ information to a frame/mental model	HSI output
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Team training
					Task training
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Task load
					Time constraint
					Procedures
				Improper control of attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress
					Task load
					Time constraint
					Team training
					Work place adequacy
					HSI output
				Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
			Incorrect frame used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Morale/motivation/attitude

					Procedures
				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Frame/mental model inappropriately rejected/ reframed when it should be preserved/ confirmed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
				No frame/mental model exists to interpret the information/situation	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Cognitive complexity
					Execution complexity
					HSI output
					Procedures
	Procedure Misinterpreted	Understanding	Incorrect/ incomplete/ inaccurate information used to understand the situation	Information available in the environment is not complete, correct, accurate, or otherwise sufficient to create understanding of the situation	HSI output
					Cognitive complexity
					Execution complexity
					Procedure quality
					Procedure availability
				Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedure quality
			Incorrect integration of data, frames, or data with a frame	Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedure quality
				Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Improper aspects of the data selected for comparison with/identification of a frame	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training

					HSI output
					Procedures
				Improper aspects of the frame selected for comparison with the data	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Incorrect or failure to match data/ information to a frame/mental model	HSI output
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Team training
					Task training
				Improper control of attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress
					Task load
					Time constraint
					Team training
					Work place adequacy
					HSI output
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Task load
					Time constraint
					Procedures
				Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
			Incorrect / incomplete / improper frame / mental model used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Morale/motivation/attitude
					Procedures
				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)

					Team training
					Task training
					Procedures
		Decision	Incorrect mental simulation or evaluation of options	Misinterpretation of procedures	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					HSI output
					Time constraint
					Task load
	Failure to Adapt procedure to the Situation	Understanding	Incorrect data used to understand the situation	Information available in the environment is not complete, correct, accurate, or otherwise sufficient to create understanding of the situation	HSI output
					Cognitive complexity
					Execution complexity
					Procedure quality
					Procedure availability
				Attention to wrong/inappropriate information	HSI output
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
				Improper data/aspects of the data selected for comparison with/identification of a frame	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedures
				Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedure quality
			Incorrect integration of data, frames, or data with a frame	Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedure quality
				Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)

						Procedures
					Improper aspects of the data selected for comparison with/identification of a frame	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						HSI output
						Procedures
					Improper aspects of the frame selected for comparison with the data	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Procedures
					Incorrect or failure to match data/ information to a frame/mental model	HSI output
						Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Procedures
						Team training
						Task training
					Working memory limitations impair processing of information	Cognitive complexity
						Execution complexity
						Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						HSI output
						Task load
						Time constraint
						Procedures
					Improper control of attention	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Stress
						Task load
						Time constraint
						Team training
						Task training
						Work place adequacy
						HSI output
					Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
				Incorrect frame used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						Morale/motivation/attitude
						Procedures

				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Frame/mental model inappropriately rejected/ reframed when it should be preserved/ confirmed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
				No frame/mental model exists to interpret the information/situation	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Cognitive complexity
					Execution complexity
					HSI output
					Procedures
	Procedure Step Omitted (Intentional)	Understanding	Incorrect integration of information, frame or information with a frame/mental model	Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedure quality
				Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Incorrect or failure to match data/ information to a frame/mental model	HSI output
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Team training
					Task training
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Task load

					Time constraint
					Procedures
				Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
			Incorrect/ incomplete/ improper frame/mental model used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Morale/motivation/attitude
					Procedures
				Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Confidence in information
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
				No frame/mental model exists to interpret the information/situation	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Cognitive complexity
					Execution complexity
					HSI output
					Procedures
		Decision	Incorrect goals or priorities	Incorrect goals selected	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedures
					Task load
					Time constraint
					Safety Culture
				Goal conflict	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures

						HSI output
						Stress due to decision
						Safety Culture
					Incorrect prioritization of goals	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						Resources
						Procedures
						Task load
						Safety Culture
					Incorrect judgment of goal success	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						Procedures
						Task load
						Time constraint
						HSI
				Incorrect mental simulation or evaluation of options	Inaccurate portrayal of action	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						Cognitive complexity
						Task load
						Time constraint
					Incorrect inclusion of alternatives	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						Task load
						Time constraint
					Misinterpretation of procedures	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						Procedures
						HSI output
						Task load
						Time constraint
					Inaccurate portrayal of the system response to the proposed action	Knowledge / experience /skill (content)
						Knowledge / experience /skill (access)
						Team training
						Task training
						Procedures
						Task load
						Time constraint
					Cognitive bias	Knowledge / experience /skill (content)

					Knowledge / experience /skill (access)
					Team training
					Task training
					Task load
					Time constraint
	Inappropriate Transfer to a Different procedure	Understanding	Incorrect integration of information, frame or information with a frame/mental model	Data not properly recognized, classified, or distinguished	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedure quality
				Improper integration of information or frames	Attention
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
				Incorrect or failure to match data/ information to a frame/mental mode	HSI output
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Procedures
					Team training
					Task training
				Working memory limitations impair processing of information	Cognitive complexity
					Execution complexity
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Task load
					Time constraint
					Procedures
				Mental manipulation of the information is inadequate, inaccurate, or otherwise inappropriate	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
				Improper control of attention	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					stress
					Task load
					Time constraint
					Team training
					Task training
					Work place adequacy
					HSI output
			Incorrect/ incomplete/ improper frame/mental model used to understand the situation	Incorrect or inadequate frame/mental model used to interpret/integrate information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training

					Morale/motivation/attitude
					Procedures
				Incorrect or inappropriate frame used to search for, identify, or attend to information	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
		Decision	Incorrect goals or priorities set	Incorrect goals selected	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedures
					Task load
					Time constraint
					Safety Culture
				Goal conflict	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					HSI output
					Stress due to decision
					Safety Culture
				Incorrect prioritization of goals	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Resources
					Procedures
					Task load
					Safety Culture
				Incorrect judgment of goal success	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					Task load
					Time constraint
					HSI
			Incorrect mental simulation or evaluation of options	Inaccurate portrayal of action	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Cognitive complexity
					Task load
					Time constraint

				Misinterpretation of procedures	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					HSI output
					Task load
					Time constraint
				Inaccurate portrayal of the system response to the proposed action	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					Task load
					Time constraint
				Cognitive bias	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Task load
					Time constraint
	Decision to Delay Action	Decision	Incorrect goals or priorities set	Incorrect goals selected	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedures
					Task load
					Time constraint
					Safety Culture
				Goal conflict	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					HSI output
					Stress due to decision
					Safety Culture
				Incorrect prioritization of goals	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Resources
					Procedures
					Task load
					Safety Culture

				Incorrect judgment of goal success	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					Task load
					Time constraint
					HSI
			Incorrect internal pattern matching	Not updating the mental model to reflect the changing state of the system	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
			Incorrect mental simulation or evaluation of options	Inaccurate portrayal of the system response to the proposed action	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Cognitive complexity
					Task load
					Time constraint
				Cognitive biases	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Task load
					Time constraint
	Inappropriate Strategy Chosen	Decision	Incorrect goals or priorities set	Incorrect goals selected	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI output
					Procedures
					Task load
					Time constraint
					Safety Culture
				Goal conflict	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					HSI output
					Stress due to decision
					Safety Culture
				Incorrect prioritization of goals	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training

					Resources
					Procedures
					Task load
					Safety Culture
				Incorrect judgment of goal success	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					Task load
					Time constraint
					HSI
			Incorrect internal pattern matching	Not updating the mental model to reflect the changing state of the system	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
				Incorrectly comparing the mental model to previously encountered situations	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Cognitive complexity
					Execution complexity
					Attention
					Task load
					Time constraint
				Cognitive biases	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Task load
					Time constraint
			Incorrect mental simulation or evaluation of options	Inaccurate portrayal of the system response to the proposed action	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Procedures
					Task load
					Time constraint
				Cognitive biases	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					Task load
					Time constraint
Action Phase	Incorrect Timing of Action	Action	Failure to execute desired action	Working memory failure	Knowledge / experience /skill (content)

			(EOO)		Knowledge / experience /skill (access)
					Task load
					Extra work load
					Team training
					Task training
					Time constraint
				Prospective memory failure	HSI
					Cognitive complexity
					Task load
					Extra work load
					Time constraint
				Divided attention	Task load
					Extra work load
					Work place adequacy
					Time constraint
			Execute desired action incorrectly	Error monitoring and correction	HSI
					Physical abilities and readiness
					Stress
					Procedures
					Time constraint
				Dual task interference	HSI
					Task load
					Extra work load
					competing or conflicting goals
					Time constraint
				Task switching interference	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Task load
					Extra work load
					Time constraint
	Incorrect operation of component / Object	Action	Failure to execute desired action (EOO)	Working memory failure	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Task load
					Extra work load
					Team training
					Task training
					Time constraint
				Prospective memory failure	HSI
					Cognitive complexity
					Task load
					Extra work load
					Time constraint
				Divided attention	Task load
					Extra work load
					Work place adequacy
					Time constraint
			Execute desired action incorrectly	Error monitoring and correction	HSI
					Physical abilities and readiness

					Procedures
					Stress
					Time constraint
				Dual task interference	HSI
					Task load
					Extra work load
					competing or conflicting goals
					Time constraint
				Task switching interference	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Task load
					Extra work load
					Time constraint
				Negative transfer / habit intrusion	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Task load
					Team training
					Task training
				Automaticity control	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Team training
					Task training
					HSI
					Task load
				Mode confusion	HSI
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
				Population stereotypes	HSI
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress
					Team training
					Task training
				Motor learning	Team training
					Task training
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
				Recognition errors	HSI
				Stimulus response compatibility	HSI
				Manual control issues	HSI
					Workplace adequacy
				Continuous control deficiencies	HSI
	Action on wrong component /	Action	Failure to execute desired action	Working memory failure	Knowledge / experience /skill (content)

	Object		(EOO)		Knowledge / experience /skill (access)
					Task load
					Extra work load
					Team training
					Task training
					Time constraint
				Prospective memory failure	HSI
					Cognitive complexity
					Task load
					Extra work load
					Time constraint
				Divided attention	Task load
					Extra work load
					Work place adequacy
					Time constraint
			Execute desired action incorrectly	Error monitoring and correction	HSI
					Physical abilities and readiness
					Procedures
					Stress
					Time constraint
				Dual task interference	HSI
					Task load
					Extra work load
					competing or conflicting goals
					Time constraint
				Task switching interference	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Task load
					Extra work load
					Time constraint
				Negative transfer / habit intrusion	Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Task load
					Team training
					Task training
				Population stereotypes	HSI
					Knowledge / experience /skill (content)
					Knowledge / experience /skill (access)
					Stress
					Team training
					Task training
				Recognition errors	HSI

Appendix C –Data Sources

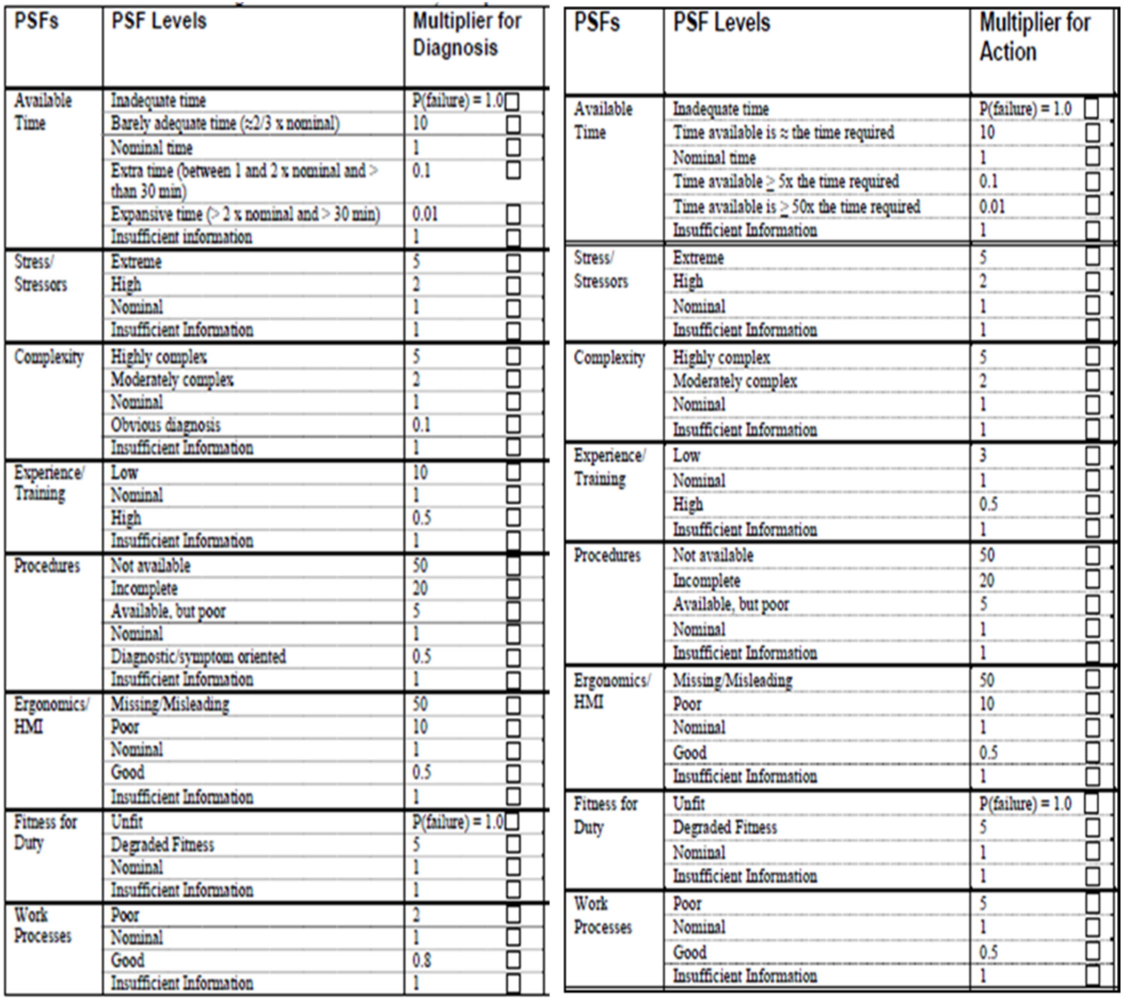
Table C1: NARA GTTs [98]

ID	GTT Description	HEP	95% t-confidence
Task Execution			
A1	Carry out a simple single manual action with feedback. Skill-based and therefore not necessarily with procedures.	0.005	0.002 – 0.01
A2	Start or reconfigure a system from the Main Control Room following procedures, with feedback. The procedures may require some diagnosis of alarms/indications before the need for the action is recognised.	0.001	N/A(only 3 data points)
A3	Start or reconfigure a system from a local control panel following procedures, with feedback.	0.002	0.0007 – 0.006
A4	Judgement needed for appropriate procedure to be followed, based on interpretation of a situation which is covered by training at appropriate intervals.	0.006	N/A (only 3 data points)
A5	Completely familiar, well designed highly practised, routine task performed to highest possible standards by highly motivated, highly trained and experienced person, totally aware of implications of failure, with time to correct potential errors.	0.0001	0.000004 – 0.002
Ensuring correct plant status and availability of plant resources			
B1	Routine check of plant status.	0.02	0.003 – 0.2
B2	Restore a single train of a system to correct operational status after a test, following procedures.	0.004	0.0008 – 0.02
B3	Set system status as part of routine operations using strict administratively controlled procedures, e.g. top up tank to correct level.	0.0007	N/A (only 3 data points)
B4	Calibrate plant equipment using procedures, e.g. adjust set-point.	0.003	0.0003 – 0.03
B5	Carry out analysis.	0.03	N/A (only 1 data point)
Alarm/Indication Response			
C1	Simple response to a range of alarms/indications providing clear indication of situation (simple diagnosis required). Response might be direct execution of simple actions or initiating other actions separately assessed.	0.0004	N/A (only 1 data point)
C2	Identification of situation requiring interpretation of complex pattern of alarms/indications.	0.2	0.15 – 0.33
Communication			
D1	Verbal communication of safety-critical data.	0.006	0.002 – 0.009

Table C2: NARA's EPCs [97]

NARA EPC ID	NARA EPC DESCRIPTION	NARA EPC Affect
1	A need to unlearn a technique and apply one which requires the application of an opposing philosophy.	24
2	Unfamiliarity, i.e. a potentially important situation which only occurs infrequently or is novel.	20
3	Time pressure.	11
4	Low signal to noise ratio.	10
5	Little or no independent checking or testing of output (when normally present)	10
6	Difficulties caused by poor shift hand-over practices and/or team co-ordination problems or friction between team members.	10
7	A means of suppressing or over-riding information or features which is too easily accessible.	9
8	No obvious means of reversing an unintended action.	9
9	Operator inexperience.	8
10	Information overload, particularly one caused by simultaneous presentation of non-redundant information.	6
11	Poor, ambiguous or ill-matched system feedback.	4
12	Shortfalls in the quality of information conveyed by procedures.	3
13	Operator under-load/boredom.	3
14	A conflict between immediate and long-term objectives.	2.5
15	An incentive to use other more dangerous procedures.	2
16	Poor environment.	8
17	No obvious way of keeping track of progress during an activity.	2
18	High emotional stress and effects of ill health.	2
19	Low workforce morale or adverse organisational environment.	2

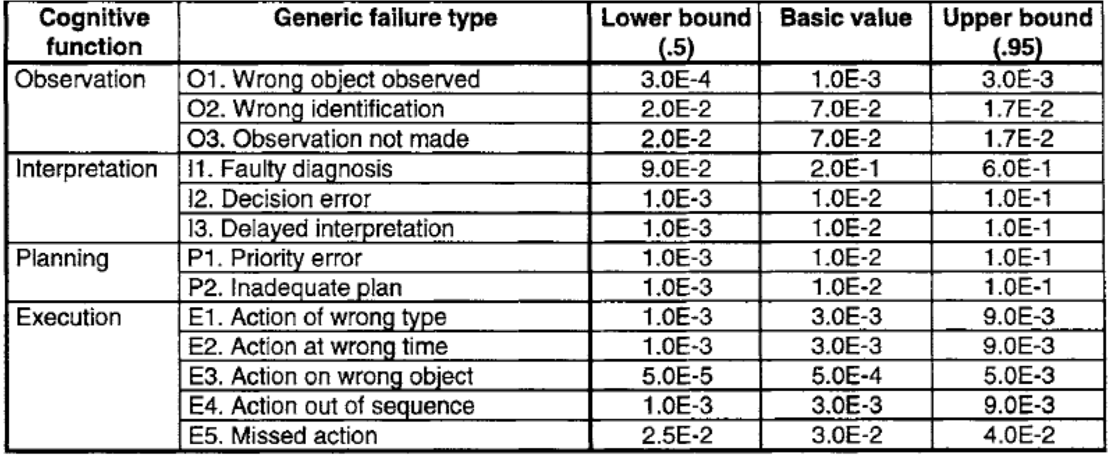
Table C3: SPAR-H PIFs and multipliers for both Diagnosis and Action [19]



PSFs	PSF Levels	Multiplier for Diagnosis
Available Time	Inadequate time	P(failure) = 1.0 ☐
	Barely adequate time (≈2/3 x nominal)	10 ☐
	Nominal time	1 ☐
	Extra time (between 1 and 2 x nominal and > than 30 min)	0.1 ☐
	Expansive time (> 2 x nominal and > 30 min)	0.01 ☐
	Insufficient information	1 ☐
Stress/ Stressors	Extreme	5 ☐
	High	2 ☐
	Nominal	1 ☐
	Insufficient Information	1 ☐
Complexity	Highly complex	5 ☐
	Moderately complex	2 ☐
	Nominal	1 ☐
	Obvious diagnosis	0.1 ☐
	Insufficient Information	1 ☐
Experience/ Training	Low	10 ☐
	Nominal	1 ☐
	High	0.5 ☐
	Insufficient Information	1 ☐
Procedures	Not available	50 ☐
	Incomplete	20 ☐
	Available, but poor	5 ☐
	Nominal	1 ☐
	Diagnostic/symptom oriented	0.5 ☐
	Insufficient Information	1 ☐
Ergonomics/ HMI	Missing/Misleading	50 ☐
	Poor	10 ☐
	Nominal	1 ☐
	Good	0.5 ☐
	Insufficient Information	1 ☐
Fitness for Duty	Unfit	P(failure) = 1.0 ☐
	Degraded Fitness	5 ☐
	Nominal	1 ☐
	Insufficient Information	1 ☐
Work Processes	Poor	2 ☐
	Nominal	1 ☐
	Good	0.8 ☐
	Insufficient Information	1 ☐

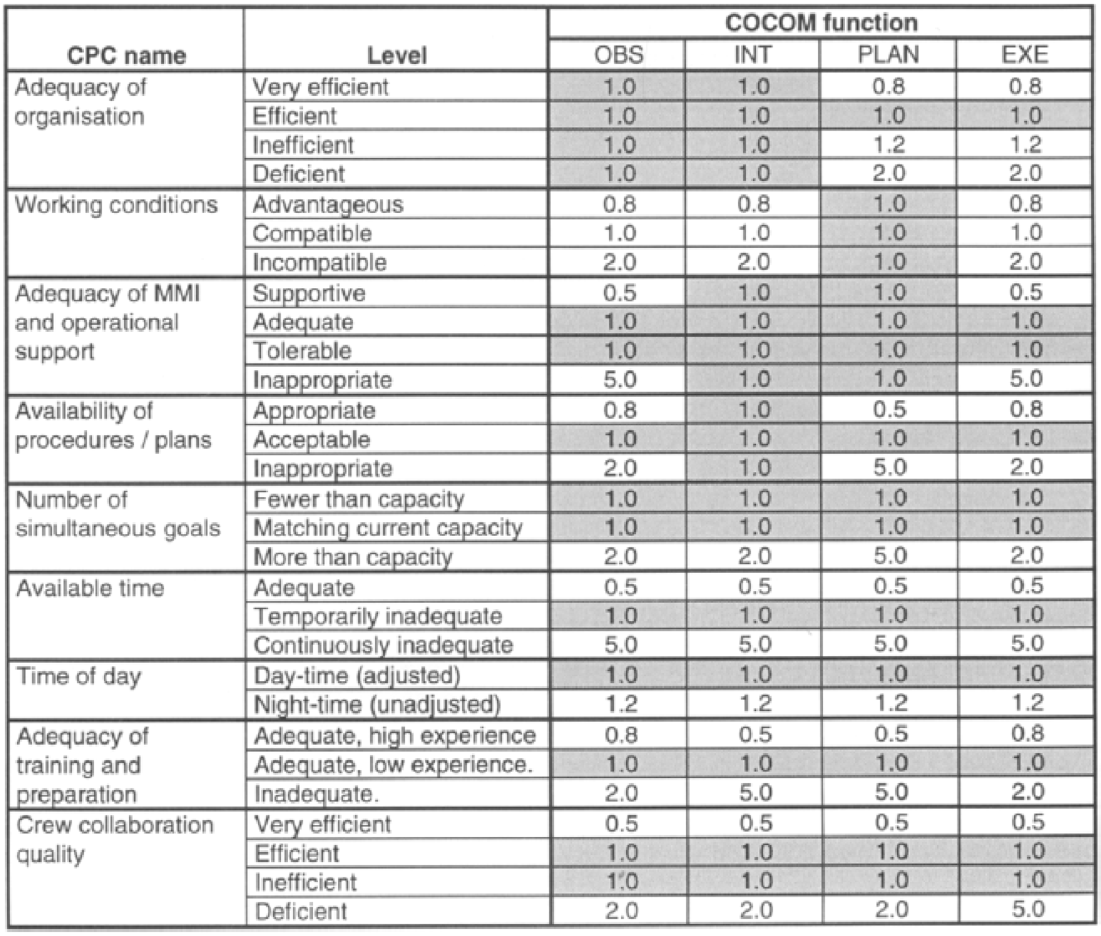
PSFs	PSF Levels	Multiplier for Action
Available Time	Inadequate time	P(failure) = 1.0 ☐
	Time available is ≈ the time required	10 ☐
	Nominal time	1 ☐
	Time available ≥ 5x the time required	0.1 ☐
	Time available is ≥ 50x the time required	0.01 ☐
	Insufficient Information	1 ☐
Stress/ Stressors	Extreme	5 ☐
	High	2 ☐
	Nominal	1 ☐
	Insufficient Information	1 ☐
Complexity	Highly complex	5 ☐
	Moderately complex	2 ☐
	Nominal	1 ☐
	Insufficient Information	1 ☐
Experience/ Training	Low	3 ☐
	Nominal	1 ☐
	High	0.5 ☐
	Insufficient Information	1 ☐
Procedures	Not available	50 ☐
	Incomplete	20 ☐
	Available, but poor	5 ☐
	Nominal	1 ☐
	Insufficient Information	1 ☐
Ergonomics/ HMI	Missing/Misleading	50 ☐
	Poor	10 ☐
	Nominal	1 ☐
	Good	0.5 ☐
	Insufficient Information	1 ☐
Fitness for Duty	Unfit	P(failure) = 1.0 ☐
	Degraded Fitness	5 ☐
	Nominal	1 ☐
	Insufficient Information	1 ☐
Work Processes	Poor	5 ☐
	Nominal	1 ☐
	Good	0.5 ☐
	Insufficient Information	1 ☐

Table C4: CREAM's generic failure types [12]



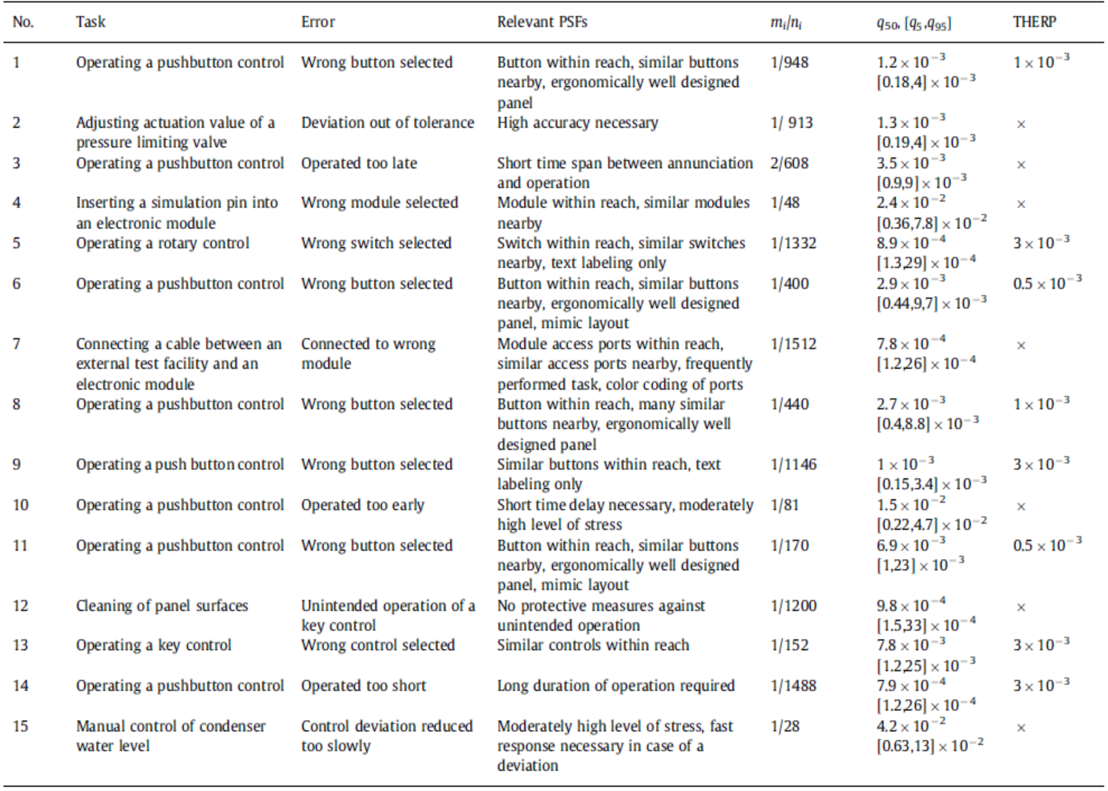
Cognitive function	Generic failure type	Lower bound (.5)	Basic value	Upper bound (.95)
Observation	O1. Wrong object observed	3.0E-4	1.0E-3	3.0E-3
	O2. Wrong identification	2.0E-2	7.0E-2	1.7E-2
	O3. Observation not made	2.0E-2	7.0E-2	1.7E-2
Interpretation	I1. Faulty diagnosis	9.0E-2	2.0E-1	6.0E-1
	I2. Decision error	1.0E-3	1.0E-2	1.0E-1
	I3. Delayed interpretation	1.0E-3	1.0E-2	1.0E-1
Planning	P1. Priority error	1.0E-3	1.0E-2	1.0E-1
	P2. Inadequate plan	1.0E-3	1.0E-2	1.0E-1
Execution	E1. Action of wrong type	1.0E-3	3.0E-3	9.0E-3
	E2. Action at wrong time	1.0E-3	3.0E-3	9.0E-3
	E3. Action on wrong object	5.0E-5	5.0E-4	5.0E-3
	E4. Action out of sequence	1.0E-3	3.0E-3	9.0E-3
	E5. Missed action	2.5E-2	3.0E-2	4.0E-2

Table C5: CREAM’s CPCs [12]



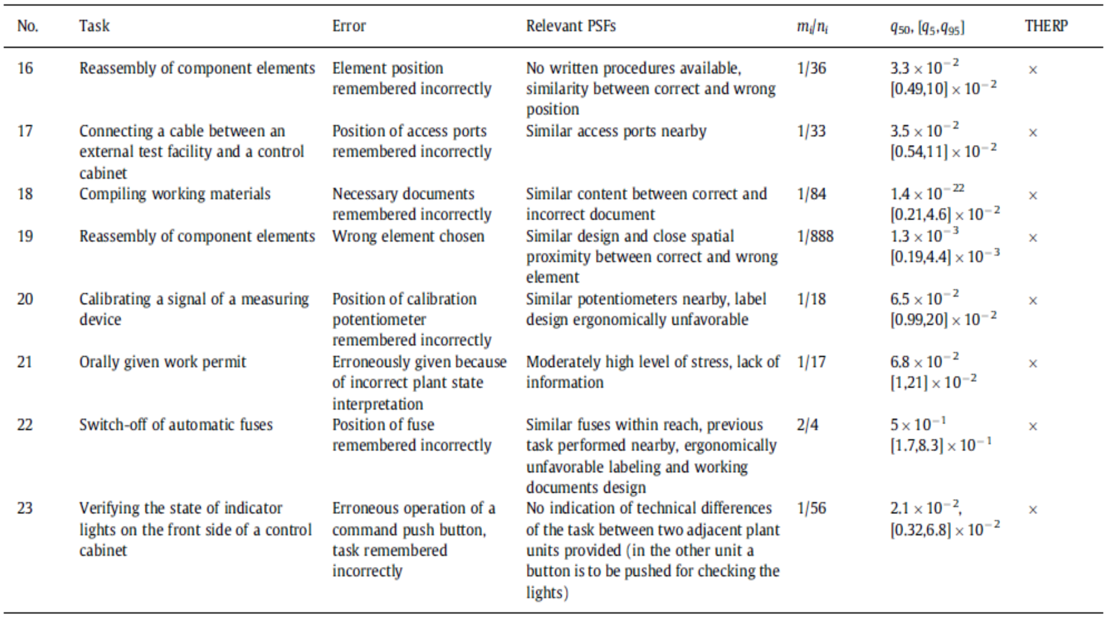
CPC name	Level	COCOM function			
		OBS	INT	PLAN	EXE
Adequacy of organisation	Very efficient	1.0	1.0	0.8	0.8
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.2	1.2
	Deficient	1.0	1.0	2.0	2.0
Working conditions	Advantageous	0.8	0.8	1.0	0.8
	Compatible	1.0	1.0	1.0	1.0
	Incompatible	2.0	2.0	1.0	2.0
Adequacy of MMI and operational support	Supportive	0.5	1.0	1.0	0.5
	Adequate	1.0	1.0	1.0	1.0
	Tolerable	1.0	1.0	1.0	1.0
	Inappropriate	5.0	1.0	1.0	5.0
Availability of procedures / plans	Appropriate	0.8	1.0	0.5	0.8
	Acceptable	1.0	1.0	1.0	1.0
	Inappropriate	2.0	1.0	5.0	2.0
Number of simultaneous goals	Fewer than capacity	1.0	1.0	1.0	1.0
	Matching current capacity	1.0	1.0	1.0	1.0
	More than capacity	2.0	2.0	5.0	2.0
Available time	Adequate	0.5	0.5	0.5	0.5
	Temporarily inadequate	1.0	1.0	1.0	1.0
	Continuously inadequate	5.0	5.0	5.0	5.0
Time of day	Day-time (adjusted)	1.0	1.0	1.0	1.0
	Night-time (unadjusted)	1.2	1.2	1.2	1.2
Adequacy of training and preparation	Adequate, high experience	0.8	0.5	0.5	0.8
	Adequate, low experience.	1.0	1.0	1.0	1.0
	Inadequate.	2.0	5.0	5.0	2.0
Crew collaboration quality	Very efficient	0.5	0.5	0.5	0.5
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.0	1.0
	Deficient	2.0	2.0	2.0	5.0

Table C6: HEP estimates from German NPP operating experience (1/4) [102]



No.	Task	Error	Relevant PSFs	m_i/n_i	q_{50}, $[q_5,q_{95}]$	THERP
1	Operating a pushbutton control	Wrong button selected	Button within reach, similar buttons nearby, ergonomically well designed panel	1/948	1.2×10^{-3} $[0.18,4] \times 10^{-3}$	1×10^{-3}
2	Adjusting actuation value of a pressure limiting valve	Deviation out of tolerance	High accuracy necessary	1/ 913	1.3×10^{-3} $[0.19,4] \times 10^{-3}$	×
3	Operating a pushbutton control	Operated too late	Short time span between annunciation and operation	2/608	3.5×10^{-3} $[0.9,9] \times 10^{-3}$	×
4	Inserting a simulation pin into an electronic module	Wrong module selected	Module within reach, similar modules nearby	1/48	2.4×10^{-2} $[0.36,7.8] \times 10^{-2}$	×
5	Operating a rotary control	Wrong switch selected	Switch within reach, similar switches nearby, text labeling only	1/1332	8.9×10^{-4} $[1.3,29] \times 10^{-4}$	3×10^{-3}
6	Operating a pushbutton control	Wrong button selected	Button within reach, similar buttons nearby, ergonomically well designed panel, mimic layout	1/400	2.9×10^{-3} $[0.44,9.7] \times 10^{-3}$	0.5×10^{-3}
7	Connecting a cable between an external test facility and an electronic module	Connected to wrong module	Module access ports within reach, similar access ports nearby, frequently performed task, color coding of ports	1/1512	7.8×10^{-4} $[1.2,26] \times 10^{-4}$	×
8	Operating a pushbutton control	Wrong button selected	Button within reach, many similar buttons nearby, ergonomically well designed panel	1/440	2.7×10^{-3} $[0.4,8.8] \times 10^{-3}$	1×10^{-3}
9	Operating a push button control	Wrong button selected	Similar buttons within reach, text labeling only	1/1146	1×10^{-3} $[0.15,3.4] \times 10^{-3}$	3×10^{-3}
10	Operating a pushbutton control	Operated too early	Short time delay necessary, moderately high level of stress	1/81	1.5×10^{-2} $[0.22,4.7] \times 10^{-2}$	×
11	Operating a pushbutton control	Wrong button selected	Button within reach, similar buttons nearby, ergonomically well designed panel, mimic layout	1/170	6.9×10^{-3} $[1,23] \times 10^{-3}$	0.5×10^{-3}
12	Cleaning of panel surfaces	Unintended operation of a key control	No protective measures against unintended operation	1/1200	9.8×10^{-4} $[1.5,33] \times 10^{-4}$	×
13	Operating a key control	Wrong control selected	Similar controls within reach	1/152	7.8×10^{-3} $[1.2,25] \times 10^{-3}$	3×10^{-3}
14	Operating a pushbutton control	Operated too short	Long duration of operation required	1/1488	7.9×10^{-4} $[1.2,26] \times 10^{-4}$	3×10^{-3}
15	Manual control of condenser water level	Control deviation reduced too slowly	Moderately high level of stress, fast response necessary in case of a deviation	1/28	4.2×10^{-2} $[0.63,13] \times 10^{-2}$	×

Table C6: Continued (2/4) [102]



No.	Task	Error	Relevant PSFs	m_i/n_i	q_{50}, $[q_5,q_{95}]$	THERP
16	Reassembly of component elements	Element position remembered incorrectly	No written procedures available, similarity between correct and wrong position	1/36	3.3×10^{-2} $[0.49,10] \times 10^{-2}$	×
17	Connecting a cable between an external test facility and a control cabinet	Position of access ports remembered incorrectly	Similar access ports nearby	1/33	3.5×10^{-2} $[0.54,11] \times 10^{-2}$	×
18	Compiling working materials	Necessary documents remembered incorrectly	Similar content between correct and incorrect document	1/84	1.4×10^{-22} $[0.21,4.6] \times 10^{-2}$	×
19	Reassembly of component elements	Wrong element chosen	Similar design and close spatial proximity between correct and wrong element	1/888	1.3×10^{-3} $[0.19,4.4] \times 10^{-3}$	×
20	Calibrating a signal of a measuring device	Position of calibration potentiometer remembered incorrectly	Similar potentiometers nearby, label design ergonomically unfavorable	1/18	6.5×10^{-2} $[0.99,20] \times 10^{-2}$	×
21	Orally given work permit	Erroneously given because of incorrect plant state interpretation	Moderately high level of stress, lack of information	1/17	6.8×10^{-2} $[1,21] \times 10^{-2}$	×
22	Switch-off of automatic fuses	Position of fuse remembered incorrectly	Similar fuses within reach, previous task performed nearby, ergonomically unfavorable labeling and working documents design	2/4	5×10^{-1} $[1.7,8.3] \times 10^{-1}$	×
23	Verifying the state of indicator lights on the front side of a control cabinet	Erroneous operation of a command push button, task remembered incorrectly	No indication of technical differences of the task between two adjacent plant units provided (in the other unit a button is to be pushed for checking the lights)	1/56	2.1×10^{-2}, $[0.32,6.8] \times 10^{-2}$	×

Table C6: Continued (3/4) [102]

No.	Task	Error	Relevant PSFs	m_i/n_i	q_{50}, $[q_5, q_{95}]$	THERP
27	Repeated discontinuous manual control of pump discharge pressure	Task not remembered	Moderately high level of stress	1/50	2.4×10^{-2} $[0.35,7.6] \times 10^{-2}$	1×10^{-2}
28	Transporting fuel assemblies with the fuel handling machine	Memorized task step not remembered, control element not operated	High level of stress due to time constraints, visualization aids temporarily unavailable, unfavorable ergonomic design of controls	1/7	1.6×10^{-1} $[0.26,4.4] \times 10^{-1}$	1×10^{-1}
29	Operating a key control	Instruction not read in procedure, task omitted	Voluminous document, long procedure with checkoff provisions	1/211	5.6×10^{-3} $[0.83,18] \times 10^{-3}$	3×10^{-3}
30	Manually operating a local valve	Valve not operated, step in a sequence of different steps not remembered	Frequently performed task	1/1470	8×10^{-4} $[1.2,27] \times 10^{-4}$	×
31	Operating a key control	Control not operated, step not remembered	Rarely performed task, enhanced level of stress due to time constraints, unfavorable ergonomic design	1/28	4.2×10^{-2}, $[0.63,13] \times 10^{-2}$	×
32	Operating a control to bypass a reactor protection signal	Step in a procedure not read, task omitted	Moderately high level of stress due to high task load	2/180	1.2×10^{-2} $[0.32,3] \times 10^{-2}$	6×10^{-3}
33	Securing a valve in open position	Step in a procedure not read, task omitted	Long procedure with checkoff provisions	$\geq 1/440$	2.7×10^{-3} $[0.4,8.8] \times 10^{-3}$	3×10^{-3}
34	Opening a valve by MCR panel controls	Failed to open, memorized task step in not remembered	Rarely performed task sequence, moderately high level of stress	1/20	5.8×10^{-2} $[0.89,18] \times 10^{-2}$	×
35	Removing a ground connection from a switchgear cabinet	Ground connection not removed, memorized step not remembered	Rarely performed task, step not described in written procedure	1/48	2.4×10^{-2} $[0.37,7.9] \times 10^{-2}$	×
37	Activation of both mid loop level measurement devices	One channel not activated, task description in procedure misinterpreted	Ambiguous task description in procedure, moderately high level of stress	1/40	2.9×10^{-2} $[0.44,9.4] \times 10^{-2}$	×

Table C6: Continued (4/4) [102]

No.	Task	Error	Relevant PSFs	m_i/n_i	q_{50}, $[q_5, q_{95}]$	THERP
24	Confirming a signal on the conventional annunciator panel in MCR	Signal not properly confirmed due to interpretation error	Signal may be triggered by maintenance work, difficulties to identify initiation criteria	4/4	9.5×10^{-1} $[6.4,10] \times 10^{-1}$	×
25	Responding to a disturbance indicator light	Wrong action taken due to interpretation error	Oral instruction ambiguous, indicator may be triggered by test activities	4/4	9.5×10^{-1} $[6.4,10] \times 10^{-1}$	×
26	Observing abnormal behavior of an indicator light	Abnormal behavior not observed	Indicator within operator's field of view, observing the indicator not part of the ongoing activities	1/1	8.4×10^{-1} $[2.3,9.9] \times 10^{-1}$	×
36	Connecting an electronic module to an external signal	Task step not remembered	Written procedure not sufficiently detailed, lack of experience	1/1	8.4×10^{-1} $[2.3,9.9] \times 10^{-1}$	×

Table C7: HEP estimates generated for level 1 tasks in US NPP through expert judgment [101]

	Task Descriptions	
(1)	During a loss-of-off-site-power transient, several failures have rendered the high pressure coolant injection (HPCI) and the reactor core isolation cooling (RCIC) systems inoperable. Core cooling can be established with either low pressure coolant injection or low pressure core spray, but pressure must be reduced first. Procedural guidelines specify manual actuation of the automatic depressurization system (ADS) to reduce pressure. What is the likelihood that the operator will fail to actuate the ADS manually within 10 minutes?	HEP* = 0.0007 LB** = 0.00006 UB*** = 0.008

* HEP = Human Error Probability
** LB = Direct Estimate Lower Uncertainty Bounds
*** UB = Direct Estimate Upper Uncertainty Bounds

(2)	During a loss-of-off-site-power transient, the generator has tripped, the reactor has scrammed, and the normal feedwater system is inoperable. According to the procedures, the reactor water level should be recovered and maintained by manually operating the reactor core isolation cooling (RCIC) system. What is the likelihood that the operator will fail to operate the RCIC system correctly?	HEP = 0.001 LB = 0.0002 UB = 0.006
(3)	During a loss-of-off-site-power transient, the generator has tripped, the reactor has scrammed, and the normal feedwater system is inoperable. According to the emergency procedures, the operator must operate the nuclear instrumentation system by inserting the source and intermediate range monitors to verify that reactor power is decreasing following the scram. What is the likelihood that the operator will fail to operate the nuclear instrumentation system correctly?	HEP = 0.0008 LB = 0.00007 UB = 0.009
(4)	One of the main steam relief valves inadvertently opens. The operator, after successfully closing the valve, is monitoring the suppression pool temperature. The indicated temperature of the suppression pool is 95°F. According to procedures, this requires that the residual heat removal (RHR) system be manually placed in the suppression pool cooling mode. What is the likelihood that the operator will fail to actuate the suppression pool cooling mode of RHR?	HEP = 0.0002 LB = 0.00002 UB = 0.003
(5)	One of the main steam relief valves inadvertently opens. The operator mistakenly thinks he has reclosed the valve; however, the valve is still open. The operator properly places the RHR system in the suppression pool cooling mode when the temperature reaches 95°F. The temperature eventually reaches 110°F. The procedure then specifies that the operator must scram the reactor manually. What is the likelihood that the operator will fail to scram the reactor?	HEP = 0.0002 LB = .00003 UB = 0.001
(6)	A transient has occurred, the high pressure coolant injection (HPCI) system is operating, and the suppression pool cooling is inoperable. The operator notices that the HPCI system has inadvertently switc to suppression pool suction. The condensate storage tank (CST) level and the suppression pool level are both normal. The operator checks and finds that the CST water is still plentiful. What is the likelihood that the operator will not realize that high suppression pool temperature could ultimately fail HPCI due to loss of net positive suction head?	HEP = 0.07 LB = 0.007 UB = 0.31
(7)	A transient has occurred, the high pressure coolant injection (HPCI) system is operating, and the suppression pool cooling system is inoperable. The operator notices that the HPCI system has automatically switch to suppression pool suction. He checks and finds that the condensate storage tank (CST) water is still plentiful. The operator realizes that high suppression pool temperature could ultimately fail HPCI. What is the likelihood that he will fail to take the appropriate action to return the system manually so that the CST is the water supply?	HEP = 0.006 LB = 0.0002 UB = 0.03
(8)	The plant is experiencing an extended station blackout (loss of on-site and off-site power) greater than 5 hours. Continued operation of the reactor core isolation cooling (RCIC) and high pressure coolant injection (HPCI) systems depends on sufficient room cooling for the equipment. What is the likelihood that the operator will fail to take precautions such as opening doors or providing other ventilation to ensure that the vital system equipment is being properly cooled?	HEP = 0.04 LB = 0.005 UB = 0.30

(9) A transient has occurred, and the reactor has failed to scram. The operator, realizing what has happened, consults the emergency procedure for dealing with an anticipated transient without scram. The procedure states that he should attempt to trip the reactor manually. The operator attempts this but is unsuccessful. The procedure then calls for him to use the standby liquid control (SLC) system. What is the likelihood that the operator will fail to initiate SLC within 5-10 minutes after he reads the procedural step telling him to do so?	HEP = 0.0001 LB = 0.00002 UB = 0.002
(10) A station blackout including total failure of the diesel generator system has just occurred. After the first immediate steps have been taken, the emergency procedures are referenced. What is the likelihood that the operator will attempt to restore off-site power before he attempts to restore power using the diesel generators?	HEP = 0.01 LB = 0.001 UB = 0.20
(11) A transient has occurred, and the reactor protection system has failed to insert the rods. All attempts to manually scram the reactor have failed. According to the procedures, the operator is now required to manually insert the rods. What is the likelihood that the operator will fail to attempt to manually insert the rods using reactor manual control?	HEP = 0.0003 LB = 0.00002 UB = 0.002
(12) A loss-of-coolant accident (LOCA) has occurred. The residual heat removal service water (RHRSW) system must be manually initiated within the first 30 minutes after the transient to obtain successful long-term decay heat removal. The emergency operating procedures contain detailed instructions on operating the RHRSW. What is the likelihood that the operator will fail to recognize that he should initiate RHRSW within 30 minutes?	HEP = 0.001 LB = 0.00009 UB = 0.03
(13) A loss-of-coolant accident (LOCA) has occurred. The residual heat removal service water (RHRSW) system must be manually initiated to obtain successful long-term decay heat removal. The emergency operating procedures contain detailed instructions on operating the RHRSW, but the operator has so much to do he fails to operate the RHRSW. After 40 minutes the operator gets a high suppression pool temperature alarm. What is the likelihood that he will then fail to diagnose the problem correctly and take steps to initiate RHRSW?	HEP = 0.002 LB = 0.0001 UB = 0.02
(14) The residual heat removal (RHR) system is providing shutdown cooling when the running RHR pump trips because of an electrical fault. The operator acknowledges that the pump tripped. Procedures state that the operator is to restore shutdown cooling. What is the likelihood that the operator will fail to attempt to restore RHR cooling within 10 minutes?	HEP = 0.0005 LB = 0.00004 UB = 0.003
(15) The high pressure coolant injection (HPCI) system and the reactor core isolation cooling (RCIC) system have automatically initiated. The plant has experienced a total loss of instrument air. The pneumatic valves that control the cooling water to HPCI and RCIC room coolers do not open on demand because of the loss of instrument air. Opening these valves requires local operation. What is the likelihood that the operator will fail to open these valves within 1 hour?	HEP = 0.03 LB = 0.005 UB = 0.39

Table C8: HEP estimates generated for levels 2 & 3 tasks in US NPP through expert judgment [101]

Task Descriptions	
(1) An operator chooses the wrong switch from a set of switches that all look similar and are identified only by labels.	HEP* = 0.004 LB** = 0.0006 UB*** = 0.03
(2) An operator chooses the wrong switch from a set of switches that all look similar and are grouped according to their functions.	HEP = 0.002 LB = 0.0003 UB = 0.01
(3) An operator chooses the wrong switch from a set of switches that all look similar and are arranged with clearly drawn mimic lines.	HEP = 0.0005 LB = 0.0001 UB = 0.003
(4) The controls in a control room are all designed so that they are moved to the right if the operator wants to turn on a component. The operator makes an error and turns a rotary control that has three or more positions to the left when he intends to turn the component on.	HEP = 0.0005 LB = 0.00008 UB = 0.004
(5) Two or more locally operated valves are not clearly labeled. In addition, they are very similar in size and shape, they are in the same state (either open or closed), and they all have been tagged in a similar fashion. (The tags are all the same color, etc.) The operator attempts to place one of these valves back in service, but he mistakenly chooses the wrong one.	HEP = 0.02 LB = 0.002 UB = 0.26
(6) A locally-operated valve is clearly and unambiguously labeled and is not located near any similar-appearing valves. The operator intends to place the valve back in service, but he mistakenly chooses the wrong one.	HEP = 0.0004 LB = 0.00004 UB = 0.003
(7) An operator reads the wrong meter in a group of meters that all look similar. They are arranged with clearly drawn mimic lines.	HEP = 0.001 LB = 0.00009 UB = 0.01
(8) An operator reads the wrong meter in a group of meters that all look similar. The meters are grouped according to their functions.	HEP = 0.006 LB = 0.0006 UB = 0.03
(9) An operator reads the wrong meter in a group of meters that all look similar and are identified only by labels.	HEP = 0.01 LB = 0.001 UB = 0.05
(10) An equipment or auxiliary operator selects the wrong circuit breaker from a group of circuit breakers that are located outside the control room. The circuit breakers are densely grouped and identified only by labels.	HEP = 0.003 LB = 0.0002 UB = 0.02
(11) A locally-operated valve has a rising stem and a position indicator. An auxiliary operator, while using written procedures to check a valve lineup, fails to realize that the valve is not in its proper position after a maintenance person has performed a procedure intended to restore it to its proper position after maintenance.	HEP = 0.003 LB = 0.0002 UB = 0.04

* HEP = Human Error Probability
** LB = Direct Estimate Lower Uncertainty Bounds
*** UB = Direct Estimate Upper Uncertainty Bounds

(12) A meter has jammed so that the pointer is stuck on the scale. When an operator reads the meter, he fails to realize that it is jammed even though the value displayed is erroneous.	HEP = 0.02 LB = 0.002 UB = 0.10
(13) An operator incorrectly reads information from a graph that is in a procedure.	HEP = 0.007 LB = 0.0005 UB = 0.03
(14) Assume that five annunciators are alarming. An operator fails to act on any of them.	HEP = 0.000002 LB = 0.0000004 UB = 0.000009
(15) Assume that ten annunciators have alarmed and an operator has responded to nine of them. The operator fails to act on the one remaining annunciator.	HEP = 0.04 LB = 0.003 UB = 0.29
(16) An operator reads a digital indicator incorrectly.	HEP = 0.00005 LB = 0.000009 UB = 0.0003
(17) A chart recorder has normal bands indicated on the scale. An operator incorrectly interprets the value shown when he scans the recorder.	HEP = 0.001 LB = 0.0001 UB = 0.008
(18) A chart recorder does not have normal bands indicated on the scale. An operator incorrectly interprets the value shown when he scans the recorder.	HEP = 0.01 LB = 0.001 UB = 0.04
(19) A meter has normal bands indicated on the scale. An operator does not notice that the meter is out of range after he performs an initial control room evaluation. No written materials are used.	HEP = 0.003 LB = 0.001 UB = 0.08
(20) An operator intends to operate a 10-position rotary selector switch. He sets it to the wrong position.	HEP = 0.003 LB = 0.0005 UB = 0.02

Table C9: SACADA taxonomy of error modes [30]

Macrocognitive Function	**Error Modes**
Monitoring/Detection	▪ **Alarm Issues**: Key alarms not detected or not responded to. ▪ **Indicator Issues**: Key parameter value not detected or incorrectly read ▪ **Others** (specify):______________________
Understanding	▪ **Misinterpreted**: critical data misinterpreted ▪ **Discredited**: critical data dismissed, discredited or discounted ▪ **Incorrect/Incomplete**: Failure to form a correct understanding or revise initial false concept. ▪ **Awareness**: lack of awareness of plant conditions ▪ **Slow**: Slow interpretation of plant parameters ▪ **Others** (specify):____________________________

Response Planning/ Procedure Implementation	o **Relevant procedural guidance available**
	  • **Not Consulted**: Failed to consult available procedure.
	  • **Following Problem**: Trouble following or using procedure
	    ○ **Wrong**: Used or transferred to a wrong procedure.
	    ○ **Misinterpreted**: Misinterpreted procedure instruction.
	    ○ **Deviated**: Incorrectly decided to deviate from the correct procedure
	    ○ **Specific/Focused Error**: Misinterpreted, omitted or incorrectly performed one or more substep of a single step.
	    ○ **Usage Rules**: Violating general usage rules. (explain):_______________
	    ○ **Others** (specify):_______________________
	  • **Not Adapted**: Failed to adapt to the situation.
	    ○ **Proactive**: Failed to take proactive action/anticipate required actions.
	    ○ **Adapt**: Failed to adapt procedures to the situation.
	    ○ **Re-evaluate**: Failed to re-evaluate/revise response as situation changed.
	    ○ **Prioritize**: Failed to correctly balance competing priorities.
	    ○ **Others** (specify):___________________________
	o **Relevant procedure or guidance not available**
	  • **Comprehensive**: Failed to consider all options.
	  • **Choice**: Made incorrect choice.
	  • **Delayed**: Delayed making decision.
	  • **Other** (specify):___________________________

Manipulation	o **Action not taken**: Forget to take required actions.
	o **Executed discrete action(s) incorrectly**
	  • **Wrong object**.
	  • **Wrong position**.
	  • **Skip**: Skipped one or more steps
	  • **Order**: Actions were performed in a wrong order
	  • **State Error**: Failed to perform prerequisite actions of the primary actions.
	  • **Others** (specify):______________________________
	o **Dynamic Manual Control**: Dynamic manual control problem.
	o **Other** (specify):__________________________________

Supervision	□ **Oversight Error**
	  ▪ **Big Picture**: Failure to maintain a big picture of the plant status and situation.
	  ▪ **Inadequate oversight**: Failure to oversee the task adequately
	  ▪ **Standards**: Failure to uphold standards
	  ▪ **Brief**: Failure to brief in accordance with standards (communication issue)
	  ▪ **Reactivity Focus**: Failure to maintain a reactivity focus (understand how events

	affect the reactor core) ▪ **Tech Specs**: failure to maintain a technical specification focus ☐ **Leadership Failure**: Failure to ensure clear lines of command. ▪ **Communicate Directions**: Inadequate in setting and communicating a direction for the crew. ▪ **Team Functioning**: Failure to promote/maintain effective team interaction ◊ **Positive Engagement**: Failure to promote positive engagement by all members. ◊ **Questioning Attitudes**: Failure to encourage a questioning attitude. ◊ **Team Roles**: Failure to promote team understanding of roles. ◊ **Poll Others**: Failure to provide opportunities for input from specific individuals. ▪ **Failure to Prioritize**: Failure to prioritize (most important things addressed first). ▪ **Poor Delegation**: Failure to delegate tasks. ▪ **Too Reactive**: Maintain a reactive posture rather than a proactive posture. ▪ **Poor Staff Loading**: Failure to utilize resources effectively. ☐ **Others** (specify):____
Teamwork	☐ **Poor Coordination**: Fail to coordinate efforts, e.g., the balance of plant operator lowered turbine load too fast for the reactor operator to support. ☐ **Lack of Ownership**: Lack of well-defined roles and responsibilities leading to lack of ownership. ☐ **Siloing**: Failure of one operator to inform the other(s) about the effects of the operator's actions ☐ **Lack of Shared Understanding**: Lack of shared understanding and direction. ☐ **Personality Conflict**: Failure to respect each other or resolve personality conflicts ☐ **Poor Inclusion/Involvement**: Some crew members dominate and others are reluctant to provide input. ☐ **Missed or inadequate brief(s)** o **Conditional briefs not held.** o **Crew update not held.** o **Poor/confusing briefs held.** ☐ **Others** (specify):___________________________________
Communication	☐ **Sender error**: Missed or incorrect communication by the sender • **Missed communication**: critical information not communicated. • **Incorrect communication** ○ **Wrong information**. ○ **Incomplete information.** ○ **Imprecise information**. ○ **Ambiguous information**: unspecific in communication content. ○ **Other** (Explain):_____________________ • **Communication standards deficiencies** ○ **Poorly directed**: Not directed to the right person. ○ **Wrong format**: Phonetics/clear terms were not used appropriately. ○ **Poor timing**: Too early or too late. ○ **Other** (explain):_____________________________ ☐ **Receiver misunderstanding** • **No repeat back**: misunderstood and did not repeat back • **Repeat back** ○ **Corrected by sender** ○ **Uncorrected by sender**

Table C10: SACADA taxonomy of error causes [30]

Overarching causes	☐ Scenario Issues: ▪ **Multiple Demands**: Multiple competing demands on attention. ▪ **Tempo**: High temp tasks. ▪ **Memory**: Demand on memory. ▪ **Stressors**: Psychological/physical stressors. ▪ **Habit Intrusion**: Highly practiced response interfered with desired response. ▪ **Personnel Shortage**: Shortage of personnel. ☐ Person Specific Issues: ▪ **Knowledge Gap**: Lack of knowledge or wrong mental model. ▪ **Slow**: slow in thinking, moving, monitoring, and communication. ▪ **Lack of Questioning Attitude**: Lack of discussion of concern. ▪ **STAR**: Fail to stop, think, act, and review. ▪ **Rushing**: Responding to real or perceived time pressure. ▪ **Attention Distracted.** ▪ **No Obvious Causes**: e.g., mental lapse and loss of focus.
Detecting alarm(s)	Background: o **Multiple Alarms**: Multiple simultaneous alarms causing distraction on individual alarm detection or pattern recognition o **Not applicable** Other Situational Issues: ☐ **Alarm Unexpected**: Alarms are triggered by more than one plant malfunctions. The alarms triggered by one of the malfunctions were either not detected or omitted. ☐ **Label/Mimic/Display Issues** ☐ **Other** (Explain):________________________
Detecting Indication	☐ **Slight Changes**: Slight change is difficult to detect. ☐ **Motivation**: No reason to check. ☐ **Labeling/Mimic/Display Issues**. ☐ **Other** (Explain):____________________________
Understanding	Alarm Issues: ☐ **Unspecific Alarms**: Individual alarms are not specific enough pointing to the system problem. ☐ **Unfamiliar/Unrecognizable Alarm Pattern**: Alarm did not show recognizable pattern in pointing to the system problem. ☐ **Spurious**: For example, sensor failure triggered the alarm. ☐ **Failed**: Key alarm failed dark. Indicator Issues: ☐ **Misleading Indications**: Subset of indicators gave misleading or conflicting information. ☐ **Missing Indications**: The primary cue was missing. Other Situational Issues: ☐ **Ambiguous/Unreliable**: Ambiguous/subtle cues. ☐ **Masked**: Masked cue. ☐ **Pre-disposed (Fake-out)**: Initial symptoms capture thinking leading to misdiagnosis. ☐ **Distributed**: Relevant information distributed over time/space. ☐ **Mismatch**: Plant response mismatch prior training/experience. ☐ **Other** (Explain):___________________________
Response planning and procedure implementation	☐ **Unfamiliar**: unfamiliar scenario. ☐ **Competing priorities**: Multiple competing goals. ☐ **Procedure-Scenario Mismatch**: Plant conditions do not match procedure assumptions. ☐ **Conflicting Guidance**: Conflicting guidance in procedures, policies, or practices. ☐ **Prior Experience**: Plant responses mismatched with prior training or experience. ☐ **Other** (Explain):__________________________
Manipulation	☐ **Complex**: Complex system dynamics. ☐ **Feedback**: Inadequate system feedback, e.g., long system response time

	☐ **Similar Controls** ☐ **Nonstandard Controls**: Operates differently from standard controls or normal conventions. ☐ **Labeling/Mimic/Display Issues**. ☐ **Other** (Explain):_______________________________
Supervision	☐ Scenario Issues: (Same as the scenario issues shown in Table B2). ☐ Person Specific: ▪ **Oversight Failure:** ◊ **Misplaced Trust**: Halo effect (inappropriate assuming that unsupervised work is sufficient). ◊ **Non-confrontational**: Disinclined to confront nonconformance. ◊ **Over Focused**: Too involved in individual tasks ▪ **Leadership Failure** ◊ **Overconfidence** ◊ **Disrespect: Disrespect of others** ▪ **General** ◊ **Knowledge Gap**: Lack of knowledge or experience/skill ◊ **Slow**: Thinking slow, moving slow, monitoring slow, and communicating slow, etc. ◊ **Lack of Questioning Attitude**: or lack of discussion of concerns. ◊ **Rushing**: Responding to real or perceived time pressure. ◊ **No Obvious Causes**: Mental lapse or loss of focus. ☐ **Other** (Explain):_______________________________
Teamwork	☐ Scenario Issues (Same as the scenario issues shown in Table B2) ☐ Team Specific: ▪ **Knowledge Gap**: The whole team collectively lacks the required knowledge ▪ **Lack of Questioning Attitude**: Lack of discussion of concern. ▪ **Lack of Familiarity**: Limited experience in working together ▪ **Cohesion Problem**: Baggage or historical issues. ▪ **Experience Mix**: Challenging mix of experience. ▪ **Personality Mix**: Challenging mix of personality types. ☐ Others (Explain):_____________________________
Communication	☐ **Too Formal**: Overly formal communication substantially delayed/distracted the crew ☐ **High Demand**: Tight communication/coordination demands within MCR. ☐ **Unclear**: Similar sounding words, e.g., increase and decrease. ☐ **Noise**: Noise makes communication difficult. ☐ **Procedure Inadequacy**: Confusable words included in the procedures such as increase and decrease. ☐ **Other** (Explain):_____________________________

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