ABSTRACT

Title of dissertation: A DATA-INFORMED MODEL OF PERFORMANCE SHAPING FACTORS FOR USE IN HUMAN RELIABILITY ANALYSIS

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Many Human Reliability Analysis (HRA) models use Performance Shaping Factors (PSFs) to incorporate human elements into system safety analysis and to calculate the Human Error Probability (HEP). Current HRA methods rely on different sets of PSFs that range from a few to over 50 PSFs, with varying degrees of interdependency among the PSFs. This interdependency is observed in almost every set of PSFs, yet few HRA methods offer a way to account for dependency among PSFs. The methods that do address interdependencies generally do so by varying different multipliers in linear or log-linear formulas. These relationships could be more accurately represented in a causal model of PSF interdependencies.

This dissertation introduces a methodology to produce a Bayesian Belief Network (BBN) of interactions among PSFs. The dissertation also presents a set of fundamental guidelines for the creation of a PSF set, a hierarchy of PSFs developed specifically for causal modeling, and a set of models developed using currently available data. The models, methodology, and PSF set were developed using nuclear

power plant data available from two sources: information collected by the University of Maryland for the Information-Decision-Action model [1] and data from the Human Events Repository and Analysis (HERA) database [2], currently under development by the United States Nuclear Regulatory Commission.

Creation of the methodology, the PSF hierarchy, and the models was an iterative process that incorporated information from available data, current HRA methods, and expert workshops. The fundamental guidelines are the result of insights gathered during the process of developing the methodology; these guidelines were applied to the final PSF hierarchy. The PSF hierarchy reduces overlap among the PSFs so that patterns of dependency observed in the data can be attribute to PSF interdependencies instead of overlapping definitions. It includes multiple levels of generic PSFs that can be expanded or collapsed for different applications.

The model development methodology employs correlation and factor analysis to systematically collapse the PSF hierarchy and form the model structure. Factor analysis is also used to identify Error Contexts (ECs) – specific PSF combinations that together produce an increased probability of human error (versus the net effect of the PSFs acting alone). Three models were created to demonstrate how the methodology can be used provide different types of data-informed insights.

By employing Bayes' Theorem, the resulting model can be used to replace linear calculations for HEPs used in Probabilistic Risk Assessment. When additional data becomes available, the methodology can be used to produce updated causal models to further refine HEP values.

A DATA-INFORMED MODEL OF PERFORMANCE SHAPING FACTORS FOR USE IN HUMAN RELIABILITY ANALYSIS

by

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2009

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Acknowledgments

At the beginning of the dissertation writing process, I had high hopes of writing thoughtful, clever acknowledgments that express how truly grateful I am for the many people who have helped make this dissertation possible. However, with the deadline for submission fast approaching, I've realized that people would rather see me graduate than to find "just the right words" to thank them. It's impossible to thank every individual who has shared time, experience, wisdom, and friendship with me over the course of this research, but I greatly appreciate everyone who has helped me through this process.

First and foremost, I'd like to thank my advisor, Professor Ali Mosleh, and the members of my dissertation committee: Professor Kent Norman, Professor Jeffrey Herrmann, Professor Linda Schmidt, and Dr. Y. James Chang. It's not often that all of the committee members show a genuine interest in the dissertation topic, yet I was fortunate enough to find five individuals who provided valuable insight and feedback. I would also like to express my appreciation to Professor Michel Cukier for his attendance in my defense.

I'd like to thank Erasmia Lois and Y. James Chang from the United States Nuclear Regulatory Commission for guidance and support during this research, and the US NRC Division of Research for the financial support that made this dissertation possible. Thank you to Ronald L. Boring, Bob Richards and Dave Gertman, for mentoring and encouragement. Thank you to all of the experts who attended the International HRA Context Workshop, for taking the time to share your knowledge. Thank you to April Whaley and Pat McCabe at the Idaho National Laboratory, for helping demystify the HERA database and for turning lemons into lemonade.

I would also like to recognize my research colleagues the University of Maryland, Center for Risk and Reliabilty: Zahra Mohaghegh, Reza Kazemi, Danielle Chrun, and Yuandan Li. I'd like to extend thanks to the following people for assistance with data analysis, which could not have been accomplished without any of them: Yuandan Li, Daisy Wise Rutstein, and Robert Mislevy at the University of Maryland; Cindy Gentillon and Dave McGrath at the Idaho National Laboratory; Russell Almond at the Educational Testing Service; Michelle Gonzales at the US Nuclear Regulatory Commission.

Thank you Heidi Butler and Prachi Kulkarni, for providing timely feedback on my many rough drafts and for helping me prepare for my defense. Thank you to my family, for making sure I never lost sight of the light at the end of the tunnel, (and for pushing me out of the way when I thought the light was attached to a train).

Finally, I would like to sincerely thank my advisor, Professor Ali Mosleh, for giving me the opportunity to work on so may interesting projects, and for having the patience to let me try several approaches before finding the one that worked, even if he knew the right approach all along. This research would not have been possible without his vision, guidance, and patience. I am awed by his ability to read people, to synthesize thoughts, and to pave a path forward (beyond the conditional probability forest). And to think, all this time I thought he was the one driving that train. He is truly a different kind of engineer and an extraordinary mentor, and it's been an honor to work with him.

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List of Acronyms and Notation

- BBN - Bayesian Belief Network
- BFA Bayesian Factor Analysis
- BOP - Balance of Plant
- EC - Error Context
- EDG - Emergency Diesel Generator
- FA - Factor Analysis
- HEP - Human Error Probability
- HERA - Human Events Repository and Analysis
- HFIS - Human Factors Information System
- HMI - Human-Machine Interface (aka HSI)
- HRA - Human Reliability Analysis
- HS - Human Success Event (in HERA)
- HSI - Human-System Interface (aka HMI)
- LOOP - Loss Of Offsite Power
- LTA - Less Than Adequate
- NPP - Nuclear Power Plant
- NRC - US Nuclear Regulatory Commission
- PFA - Principal Factor Analysis
- $Pr(a)$ - Probability of a
- $Pr(\overline{a})$. - Probability of *not a*
- $Pr(a|b)$ - Probability of a given b
- PRA - Probabilistic Risk Assessment / Probabilistic Risk Analysis
- PIF - Performance Influencing Factor (aka PSF)
- PPA - Physical and Psychological Abilities
- PSF - Performance Shaping Factor (aka PIF)
- XHE - Human Failure Event (in HERA)
- $|X|$ - The absolute value of X.

Chapter 1

Overview of Dissertation and its Contributions

1.1 Dissertation Overview

Human Reliability Analysis (HRA) is a systematic approach to reducing the likelihood and consequences of human errors in complex systems. It is the aspect of Probabilistic Risk Assessment (PRA) used to incorporate human risks into system safety analysis. HRA is an essential component of risk-informed decision making in industries such as nuclear power, space exploration, and aviation.

There are many HRA methodologies that can used to identify and analyze the causes and consequences of human errors. HRA methods also offer a way to assess Human Error Probabilities (HEPs). Many HRA methods use Performance Shaping Factors (PSFs), also called Performance Influencing Factors (PIFs), to represent the causes of human errors and to calculate HEPs.

The term PSF encompasses the various factors that affect human performance and change the likelihood of a human error. There are more than a dozen HRA methods that use PSFs, but there is not a standard set of PSFs used in the methods. This dissertation introduces a hierarchical set of PSFs that can be used for both qualitative and quantitative analysis in the next generation of HRA methods. The PSF hierarchy will allow analysts to combine different types of data and will therefore make the best use of the limited data in HRA.

There are many possible combinations of PSFs that can be linked to human error event. This dissertation introduces a methodology to develop a model that characterizes the interdependencies among the PSFs. The proposed methodology uses factor analysis to discover patterns of variance and suggests Bayesian techniques to link these patterns to human error. The result is a systematic way to select PSFs and define their interrelationships with respect to human performance in different aspects of human-machine interaction.

This research is expected to influence how the HRA community gathers data and how the community uses the data available now. Because of data limitations and the dynamic nature of HRA, the importance of this work is rooted in the methodology for creating the model and not necessarily in the models presented. The methodology allows the initial models to be updated as additional data becomes available. Ideally, future models will be incorporated into HRA methodologies to produce more accurate HEP estimates.

For applications outside of the nuclear industry, the model may have to be adapted to contain the correct PSFs associated with each industry. For example, in space exploration, the set of PSFs may contain factors related to reduced gravity. This methodology presents the concepts that can be used to create a model, but a complete set of PSFs for every industry is outside the scope of this research. The resulting BBN model is limited to commercial nuclear power applications, but given the generic nature of the majority of the PSFs, the methodology is applicable to most human-machine interaction tasks. This dissertation provides guidance for adapting the models for specific applications outside of commercial nuclear power.

The products of this research can be summarized as follows.

- Four events analyzed in HERA and a data coding scheme for information from the HERA database [2];
- A set of fundamental principles/guidelines for development of future PSF sets and refinement of PSFs used in current HRA methods;
- A hierarchical set of PSFs that aggregates knowledge from the PSFs in the HERA database and from multiple HRA methods;
- Data-driven insights about the relationships among the PSFs and between PSFs and human error events;
- A novel application of factor analysis to identify patterns among PSFs linked to human error events;
- The concept of Error Contexts (ECs) that links patterns of PSFs to the probability of error;
- A methodology to construct a Bayesian Belief Network causal model of PSF interdependencies using expert judgment and available data;
- A Bayesian technique for estimation of HEPs from the causal models.

1.2 Chapter 1 Summary

Chapter 1 provides a brief overview of the dissertation and a review of the contributions of the research. Chapter 2 gives background material and discusses the current state of HRA. Chapter 3 introduces the data sources used in this research and provides details about how data was organized. Chapter 3 also introduces a set of fundamental requirements / guidelines for systematically identifying and defining PSFs. The full PSF hierarchy developed using these guidelines is also presented in Chapter 3. Chapter 4 provides comprehensive definitions and examples for the PSFs in the hierarchy. Chapter 5 contains the methodology suggested to develop BBNs and Chapter 6 presents three models created by applying different aspects of the methodology. Chapter 7 summarizes the major points in the dissertation and suggests directions for future research.

1.3 Chapter 2 Summary

Chapter 2 provides an introduction to the research topic, including the background and motivation for the research. It provides a brief introduction to current HRA practices and discusses the current challenges in the industry. The chapter contains a discussion of a few relevant HRA methods, their PSF sets, and their methodology to calculate HEPs.

1.4 Chapter 3 Summary

Chapter 3 introduces a new PSF hierarchy suitable to be used in both qualitative and quantitative analysis. The PSF hierarchy is intended to be used in next-generation HRA analyses and models. The chapter also introduces a set of fundamental principles that must be met by any set of PSFs used in HRA.

Chapter 3 begins with a discussion of why the HRA field needs new set of PSFs and why the set needs to be hierarchically organized. Chapter 3 then describes HERA and additional data sources used in this research and explains how data was reorganized for use in the analysis. This research is the first application of the data provided in the Human Events Repository and Analysis (HERA) database, so Chapter 3 also introduces a data collection scheme to translate HERA data into a form suitable for quantitative analysis.

The PSF fundamental principles are properties of the ideal PSF set for use in HRA. These guidelines were developed from insights gathered during development of the data collection scheme. The fundamental principles have implications in terms of how the HRA field defines and uses PSFs. Two of the principles, definitional orthogonality and value neutrality, are properties of the individual PSFs. Consistent sub-event parsing and a clearly defined unit of analysis, are properties of the analysis methodology. The addition of behaviors/metrics bridges the divide between the individual PSFs and the methodology. The introduction of the set of necessary principles represents the first attempt to create a standard set of rules for development of a PSF set.

The full PSF hierarchy is introduced at the end of the chapter. The PSF hierarchy presented is the first set of PSFs designed for use in a causal model. The PSF set combines PSFs from the data sources with PSFs from many current HRA methods to create a super-set that is suitable to be used in both qualitative and quantitative analysis. The PSF set is organized in a hierarchy that can be collapsed and expanded to suit different analysis goals.

1.5 Chapter 4 Summary

Currently there is no standard terminology used in HRA methods. Various HRA methods may use different terminology for similar concepts or similar terminology for different concepts. One goal of the PSF set provided is to define a standard set of terms that can be used by next generation HRA methods. In Chapter 4, the PSFs included in the new PSF hierarchy are defined to ensure consistent interpretation of the PSFs. The chapter provides a comprehensive definition for each PSF, a list of similar terms used in current HRA methods, and examples from the available data.

The PSF set contains several elements that improve upon the PSFs used in current HRA methods. The term "Fitness for Duty" is present in many HRA methods, yet in the nuclear industry it has a strong negative connotation that implies that the worker willfully disregards rules and/or lacks concern for safety (e.g., alcohol use, sleeping at the control panel, etc). The PSF set contains *Physical and Psychological Abilities (PPA)*, which encompasses what many HRA methods intend to capture in Fitness for Duty, but does so without the negative bias associated with the term. PPA includes impairment, which is rarely seen in a power plant, but it also includes factors that may contribute to reduced cognitive functioning, but which are unavoidable consequences of hiring human workers (e.g., fatigue, circadian rhythms, physical fitness, and emotional states).

The PSF set is linked to metrics and behaviors, such as compliance and prioritization, that are observable indicators of unobservable PSFs. These behaviors are included in some HRA methods as a “Work Practices or Processes” PSF, but this is not a true PSF, rather a set of visible behaviors. The inclusion of behaviors linked to in the PSF hierarchy is expected to produce more consistent interpretation among HRA experts and increased reproducibility of HRA results.

1.6 Chapter 5 Summary

Chapter 5 proposes a methodology for developing and quantifying a data-informed Bayesian Belief Network of PSFs. Chapter 5 covers the mathematical techniques that are used to systematically collapse the hierarchy to determine the optimal PSFs for use in a model. It discusses how correlation and factor analysis are used to develop the model structure and how the quantitative techniques can be used to create a mixed model based on expert judgment and available data. The methodology also considers the special challenges involved with using binary data.

Chapter 5 also introduces the concept of Error Contexts (ECs). ECs are groups of PSFs that together contribute to greater increases in HEPs than would the individual PSFs acting alone. The patterns of variance that form ECs are identified through a novel applications of factor analysis, which has not previously been used to identify patterns in observed human performance data and link them to error. These error contexts are incorporated into the model and subsume some of the links established by correlation analysis. Model quantification is accomplished through frequency estimates, regression analysis, or by developing conditional probabilities from correlation values and marginal probabilities.

The methodology presented is a novel assembly of mathematical techniques used to produce causal models of error. The flexible methodology allows analysts to develop different types of models by applying different combinations of the analysis techniques.

1.7 Chapter 6 Summary

Chapter 6 presents three models for understanding how specific PSFs work together to produce human errors. Each model represents a different application of the methodology introduced in Chapter 5. The first model presented is a high-level model that covers how the six main aspects of the socio-technical system interact to produce error. This "6-Bubble" model aggregates the available data into the six components of the socio-technical system in order to maximize use of the available data. The "6-Bubble" model visually displays correlations among the six categories.

The second model, the "Mixed Expert/Data Model" (MEDM) is a more comprehensive model of PSFs that includes the causal relationships among over 30 of the PSFs. The MEDM was created by applying quantitative analysis to the PSFs that had sufficient data to be included in the analysis. The remainder of the model was created using expert information. This model is provided to demonstrate how the methodology introduced in Chapter 5 can be used to improve upon or validate existing expert models.

The third, "9-Bubble" model contains a reduced set of PSFs with connections to specific Error Contexts; this model is quantified based on available data. Chapter

6 also provides guidance on how to gather additional data to improve the quality of the probability estimates. The models presented offer an alternative to using linear or log-linear calculations to estimate HEPs. These models are the first HRA models developed to quantify relationships among the PSFs.

1.8 Chapter 7 Summary

Chapter 7 covers many possible directions that this research could take. It discusses several potential next steps for the research. Chapter 7 also discusses changes that have been implemented in the HERA database as a result of this works.

Chapter 2

Introduction

2.1 Motivation

In recent years, several high-profile accidents and incidents involving human error have pushed the study of human performance into the spotlight. A fatal runway overrun occurred in August 2006 in Lexington, KY occurred when the pilot attempted to take off from the incorrect runway. Human errors on the part of the pilots and the air traffic controller contributed to the crash [3]. Poor safety culture at NASA contributed poor decision making in the 2003 Columbia space shuttle accident, A combination of inexperienced personnel, insufficient management oversight, and poor communication contributed to misunderstanding of the severity of the impact of the foam tile that ultimately resulted in loss of the shuttle and flight crew [4]. Unfortunately, these are not isolated incidents. Human error is a leading contributor to accidents and near-misses in many industries. An estimated 80% of industrial accidents are attributable to human error. This statistic holds beyond the nuclear industry; examples can be found readily in offshore oil drilling [5], marine [6], finance [7], etc.

Humans play a role in every aspect of complex systems. They design and manufacture the hardware, software, and interfaces between human and the system. Humans are also responsible for the operation and maintenance of these systems. Humans play a substantial role in ensuring system safety [8]. Therefore it is important to include human elements in risk assessment of complex systems.

2.2 Significance of Human Error

Failures in complex systems, such as nuclear power and aviation, must be extensively studied due to the potentially catastrophic results of such failures. The primary reason for studying risk is the preservation of resources and lives. The desire to preserve human life is self-explanatory, but failure of any engineering system can have a wide range of additional consequences for the system owners, operators, designers, and even the public at large. In many systems there may be financial consequences; the cost of repairing or replacing the system may be high and a company could have reduced earnings while a system is out of service. In addition to current profits, a company may face future financial consequences, suffer from a lack of public confidence, and lose opportunities for growth. An inopportune system failure could cause a company to lose its initial investment in the system, lose system data, or lose the window of opportunity for system performance (e.g., canceled space shuttle launches). A successful HRA program can prevent or reduce many of these consequences by reducing opportunities for human actions to lead to failure.

2.3 Human Reliability Analysis Overview

Human Reliability Analysis (HRA) is an aspect of risk analysis concerned with systematically identifying and analyzing the causes and consequences of human errors. It is used to incorporate human risks into system safety analysis as part of an informed approach to reducing overall risk. HRA is an essential component of Probabilistic Risk Assessment (PRA) for complex systems such as nuclear power plants. HRA is used to understand and assess how humans affect system risks, with the ultimate goal of reducing the likelihood and consequences of human errors.

There are numerous HRA methods available that provide guidance for identification human errors and assessment of Human Error Probability (HEP). Of the various HRA methods, some are concerned primarily with systematic identification of observable behaviors, some attempt to quantify the probability of human error based on the situational context, and others attempt to model the human and the human's interactions with the system [9]. Different HRA methods view human error as the cause of an event, the event itself, or as the outcome of an event [10]. Human-system interactions can be broken down into separate facets related to the human, machine & situational characteristics. First generation HRA methods considered human behavior and machine performance as the two main factors in human-system interactions, and both elements were generally treated as deterministic processes. More recently, the effects of the human decision making and the relationship between the situation and human cognition have been incorporated into system analysis.

As systems are becoming more complex, the associated system failures are becoming more complicated. The increasing number of machines and people involved in systems necessitates a way to represent inputs to human cognition. To accomplish this, many current HRA methods use Performance Shaping Factors (PSFs) to describe many aspects of the human-system interaction. PSFs are used to represent the situational contexts and causes affecting human performance in different systems.

2.3.1 Performance Shaping Factor Overview

Loosely defined, a Performance Shaping Factor is any factor that enhances or degrades human performance and thus has an impact on the likelihood of error. In HRA, PSFs are used to represent the various factors that influence individual behavior and decision making. PSFs are used to represent how the situation, machine, organization, and personal characteristics influence individual performance. Currently there is no standard set of PSFs used in HRA methods, but most sets use PSFs identified in human performance literature. Personal factors include fatigue [11], motivation [12], attitude [13], attention [11], personality [11], experience [14, 11] and knowledge [14, 11]. Additional factors include management [15], teams [15, 16], communication [14, 17], leadership [18], safety culture [19], training [14, 11], environment [12], ergonomics [20], time [21] and workload [15].

PSFs are used to meet multiple goals in HRA and the study of human performance. PSFs are used to pin-point positive or negative influences on human performance and to predict conditions that lead to human errors. Several HRA methods use the state (level of influence) of the PSFs to estimate HEPs or to gain qualitative insight about the scenario. PSF states are defined on different scales depending on the selected method, but they generally range from low to high influence. HRA methods generally provide guidance as to how to assess the state of a PSF through direct measurement or extrapolation.

2.3.2 PSF Use in Current HRA Models

Many HRA methods use PSFs to estimate HEPs [10, 22, 23, 24, 25, 26]. This section contains a brief review of four HRA methods that offer specific guidelines to assess HEPs for use in PRA models. THERP [22] was one of the first HRA methods used in the nuclear industry. SLIM-MAUD [23] allows users to define the PSFs to be used in quantification, and CREAM [10] includes limited causal modeling in the structure. SPAR-H [24] is currently used for HRA analysis in over 70 nuclear power plants in the United States.

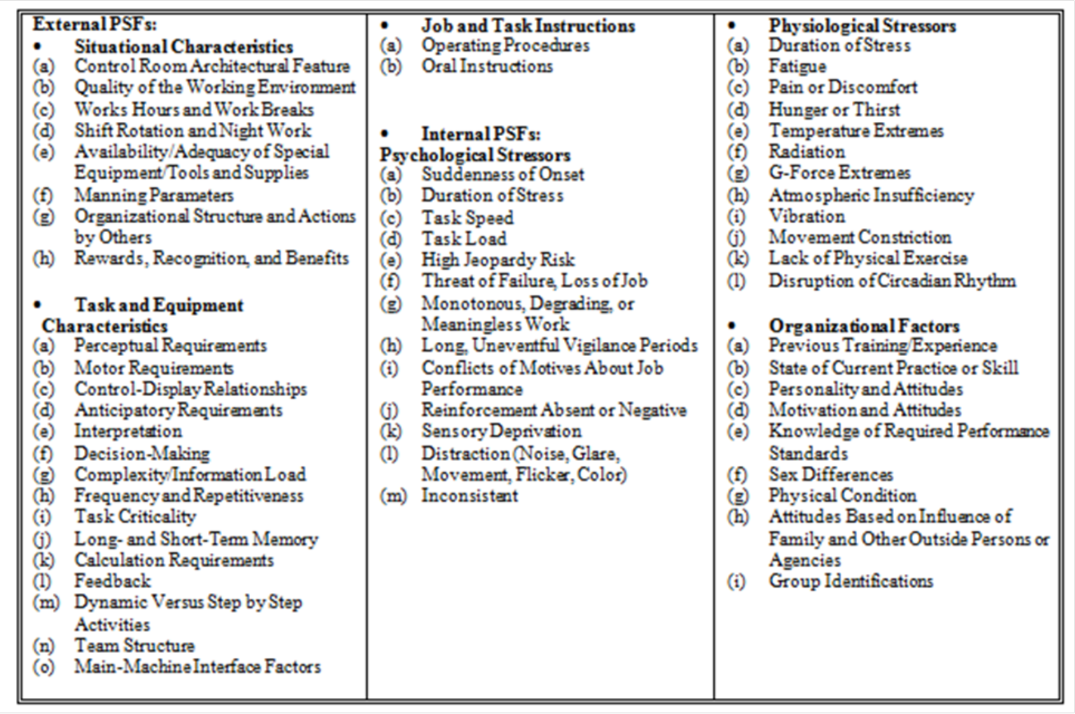
2.3.2.1 THERP

THERP (Technique for Human Error Rate Prediction) [22, 27] was initially developed and used by Sandia National Laboratories in 1961 for defense related HRA analyses. It was used to perform HRA in one of the first applications of PRA in the nuclear industry, WASH-1400 [28].

The list of PSFs in THERP is presented in Table 2.1. However, only three of the identified PSFs are used in HEP calculation. These are: tagging levels (of components or controls), experience, and stress.

THERP is used to calculate the probabilities of the following types of errors:

Table 2.1: PSFs used in the THERP method



External PSFs:

- **Situational Characteristics**
  - (a) Control Room Architectural Feature
  - (b) Quality of the Working Environment
  - (c) Works Hours and Work Breaks
  - (d) Shift Rotation and Night Work
  - (e) Availability/Adequacy of Special Equipment/Tools and Supplies
  - (f) Manning Parameters
  - (g) Organizational Structure and Actions by Others
  - (h) Rewards, Recognition, and Benefits
- **Task and Equipment Characteristics**
  - (a) Perceptual Requirements
  - (b) Motor Requirements
  - (c) Control-Display Relationships
  - (d) Anticipatory Requirements
  - (e) Interpretation
  - (f) Decision-Making
  - (g) Complexity/Information Load
  - (h) Frequency and Repetitiveness
  - (i) Task Criticality
  - (j) Long- and Short-Term Memory
  - (k) Calculation Requirements
  - (l) Feedback
  - (m) Dynamic Versus Step by Step Activities
  - (n) Team Structure
  - (o) Main-Machine Interface Factors
- **Job and Task Instructions**
  - (a) Operating Procedures
  - (b) Oral Instructions
- **Internal PSFs:**

Psychological Stressors

- (a) Suddenness of Onset
- (b) Duration of Stress
- (c) Task Speed
- (d) Task Load
- (e) High Jeopardy Risk
- (f) Threat of Failure, Loss of Job
- (g) Monotonous, Degrading, or Meaningless Work
- (h) Long, Uneventful Vigilance Periods
- (i) Conflicts of Motives About Job Performance
- (j) Reinforcement Absent or Negative
- (k) Sensory Deprivation
- (l) Distraction (Noise, Glare, Movement, Flicker, Color)
- (m) Inconsistent

- **Physiological Stressors**
  - (a) Duration of Stress
  - (b) Fatigue
  - (c) Pain or Discomfort
  - (d) Hunger or Thirst
  - (e) Temperature Extremes
  - (f) Radiation
  - (g) G-Force Extremes
  - (h) Atmospheric Insufficiency
  - (i) Vibration
  - (j) Movement Constriction
  - (k) Lack of Physical Exercise
  - (l) Disruption of Circadian Rhythm
- **Organizational Factors**
  - (a) Previous Training/Experience
  - (b) State of Current Practice or Skill
  - (c) Personality and Attitudes
  - (d) Motivation and Attitudes
  - (e) Knowledge of Required Performance Standards
  - (f) Sex Differences
  - (g) Physical Condition
  - (h) Attitudes Based on Influence of Family and Other Outside Persons or Agencies
  - (i) Group Identifications

- Screening and detection of system abnormalities (Screening Tables[1] 20-1 and 20-2).
- Diagnosis and identification of the causes of system abnormalities (Diagnosis Tables 20-3 and 20-4).
- Omitted actions, including actions in procedure preparation, use of a specified procedure (i.e., administrative control), execution of a procedure step, and providing an oral instruction (Tables 20-5 to 20-8).
- Writing down incorrect information (Table 20-5).
- Acting on a wrong object; this includes reading from an unintended display, acting on an unintended control, and unintended control actions (e.g., turn a control the

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[1] Table numbers in this section refer to tables in the THERP documentation [22]

wrong direction) (Tables 20-9 to 20-14).

THERP models a number of types of Errors of Omission (EOOs) and Errors of Commission (EOCs). EOOs modeled in THERP relate to actions in procedure preparation, use of a specified procedure (i.e., administrative control), execution of a procedure step, and providing an oral instruction (in Tables 20-5 to 20-8). The EOCs modeled in THERP include writing down incorrect information (Table 20-5) and acting on a wrong object (Tables 20-9 to 20-14).

With respect to cognitive error modeling, THERP uses available time to determine the probabilities of diagnosis failure. No further breakdown in terms of specific cognitive or decision errors is offered.

THERP is used to calculate HEPs through a number of steps:

1. **Determine probability of human error**. Construct the HRA Event Tree (ET). For each branching point of the HRA ET, use the HEP search scheme to identify the likely human errors and the corresponding nominal HEPs as well as the uncertainty bounds.

2. **Identify factors/interactions affecting human performance**. Assess the effect of the tagging levels, experience, and stress on the HEPs as well as the uncertainty bounds of the HEPs.

3. **Quantify effects of factors/interactions**. Assess the levels of task dependencies based on the five-level dependency scale specified by THERP. Such dependencies would affect the task HEPs.

4. **Account for probabilities of recovery from errors**. Assess the possible recovery branches in the HRA ET and assess the success probabilities.

5. **Calculate human error contribution to probability of system failure**. Determine the success and failure consequences within the HRA ET and calculate the final HEP of the HRA ET.

2.3.2.2 SLIM-MAUD

SLIM-MAUD (Success Likelihood Index Method using Multi-Attribute Utility Decomposition)[23] does not have a fixed set of PSFs used in calculating HEPs, rather it allows the analyst to identify PSFs based on the situation being analyzed.

The quantification steps of SLIM-MAUD are as follows:

1. **Modeling and specification of PSFs**. Experts identify the PSFs relevant to the event of interest.

2. **Weighting the PSFs**. Experts weight the effect of each PSF.

3. **Rating the PSFs**. Experts assess the state of each PSF.

4. **Calculating the Success Likelihood Indexes (SLIs)**. The values of SLIs are calculated using (2.1).

$$SLI = \sum(NormalizedWeight(PSF_i) \cdot State(PSF_i)) \tag{2.1}$$

5. **Conversion of the SLIs to probabilities**. Equation (2.2) is used to calculate the HEPs in SLIM-MAUD.

$$Log(1 - HEP) = a \cdot SLI + b \tag{2.2}$$

Using at least two sets of known HEPs and SLIs as reference points, the constants "a" and "b" can be obtained. Using the same equation (2.2) and replacing the SLI by the SLI of the task of interest, the HEP of the task can be calculated.

6. **Calculation of uncertainty bounds**. Perform sensitivity analysis by changing PSF weights and ratings to determine the upper bound and lower bound of SLI in turn determining the upper bound and lower bound of HEPs.

2.3.2.3 CREAM

CREAM (Cognitive Reliability and Error Analysis Method) [10] was developed for general applications and is based on the Contextual Control Model (COCOM) [29] which, from the information processing perspective, has emphasized the identification and calculation of cognitive errors. The method has been used in two recent NASA PRAs (Space Shuttle, and an earlier version of the International Space Station).

CREAM provides detailed instructions for both predictive and retrospective analyses. For the predictive task analyses, a number of "basic human activities" are identified (e.g., monitoring, comparing, and execution). Each task can be decomposed into a number of such basic human activities. Each basic human activity corresponds to a few likely error modes; this provides the mechanism for predictive task analysis. The method provides a list of nine PSFs (Table 2.2) and there is

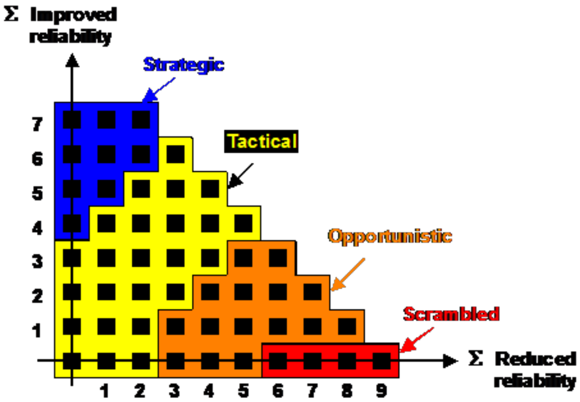


Figure 2.1: CREAM guidance for HEP estimation based on the state of 9 PSFs

an implicit causal model for relating the PSFs to certain modes of response. For retrospective analyses, CREAM provides a number of tables that allow analysts to trace back the root causes of a human error.

Table 2.2 contains the CREAM PSFs. CREAM provides a two-level approach to calculate HEPs: a basic method and an extended method. CREAM also provides simple rules to determine the HEP range of a task based on the combined PSFs' states.

The basic method can be used for task screening. The type of "control mode" is identified by through Figure 2.1 and the nine PSFs' values/states are assessed using Table 2.2. The HEP ranges for the four types of control modes are:

$5E-6 < HEP(Strategic) < 1E-2$

$1E-3 < HEP(Tactical) < 1E-1$

$1E-2 < HEP(Opportunistic) < 5E-1$

$1E-1 < HEP(Scramble) < 1$

The extended method is for performing more detailed HEP assessments. The extended procedure includes the following steps:

PSF	PSF State	Expected Effect on Performance Reliability
Adequacy of Organization	Very Efficient	Improved
	Efficient	Not significant
	Inefficient	Reduced
	Deficient	Reduced
Working Conditions	Advantageous	Improved
	Compatible	Not significant
	Incompatible	Reduced
Adequacy of HMI and operational support	Supportive	Improved
	Adequate	Not significant
	Tolerable	Not significant
	Inappropriate	Reduced
Availability of procedures/plans	Appropriate	Improved
	Acceptable	Not significant
	Inappropriate	Reduced
Number of simultaneous goals	Fewer than capacity	Not significant
	Matching current capacity	Not significant
	More than capacity	Reduced
Available time	Adequate	Improved
	Temperately inadequate	Not significant
	Continuously inadequate	Reduced
Time of day	Day-time	Not significant
	Night time	Reduced
Adequacy of training and preparation	Adequate, high experience	Improved
	Adequate, limited experience	Not significant
	Inadequate	Reduced
Crew collaboration quality	Very efficient	Improved
	Efficient	Not significant
	Inefficient	Not significant
	Deficient	Reduced

Table 2.2: PSFs used in the CREAM method

1. **Describe the task or task segments to be analyzed and perform task decomposition that breaks the task into a number of subtasks.** Each subtask can be matched to one of the fifteen pre-specified cognitive activities (see Table 2.3).

2. **Identify the type of cognitive activity for each sub-task**.

3. **Identify the associated human function of each sub-task**. Four types of human functions are identified: observation, interpretation, planning, and execution.

4. **Determine the basic HEPs for all sub-tasks**. A number of failure modes are identified. Each failure mode is associated with a basic HEP and uncertainty bound (see Table 2.3; the uncertainty bounds are not shown in the table).

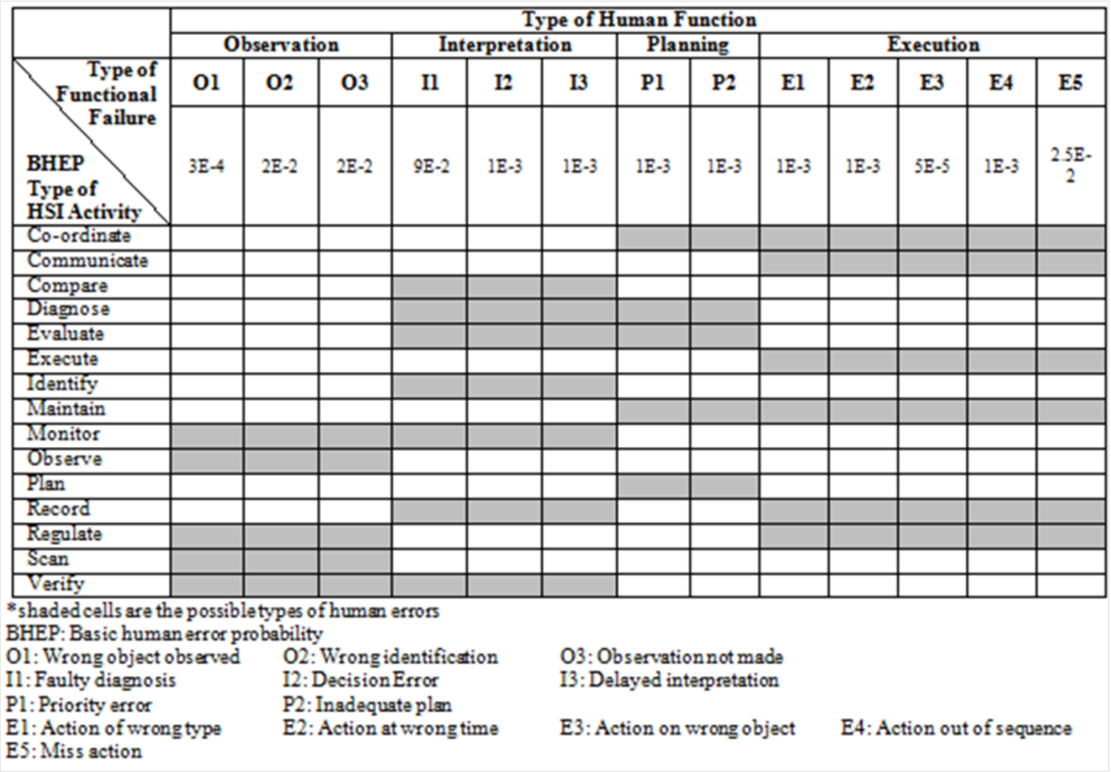
5. **Determine the PSFs' effect on the sub-tasks' HEPs.** Adjust the base HEPs by multiplying by the adjustment factors based on the states of the PSFs (see Table 2.4).

6. Calculate the task HEP based on the HEPs of sub-tasks.

2.3.2.4 SPAR-H

The SPAR-H (Standardized Plant Analysis Risk-Human Reliability Analysis) method was developed to estimate HEPs for use in the SPAR PRA models used in commercial nuclear power plants. SPAR-H is used as part of PRA in over 70 US nuclear power plants. SPAR-H also is the main model behind the Human Event

Table 2.3: CREAM activity types



	Type of Human Function												
	Observation			Interpretation			Planning		Execution				
Type of Functional Failure	O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5
BHEP Type of HSI Activity	3E-4	2E-2	2E-2	9E-2	1E-3	1E-3	1E-3	1E-3	1E-3	1E-3	5E-5	1E-3	2.5E-2
Co-ordinate							▨	▨	▨	▨	▨	▨	▨
Communicate									▨	▨	▨	▨	▨
Compare				▨	▨	▨							
Diagnose				▨	▨	▨	▨	▨					
Evaluate				▨	▨	▨	▨	▨					
Execute									▨	▨	▨	▨	▨
Identify				▨	▨	▨							
Maintain							▨	▨	▨	▨	▨	▨	▨
Monitor	▨	▨	▨	▨	▨	▨							
Observe	▨	▨	▨										
Plan							▨	▨					
Record				▨	▨	▨			▨	▨	▨	▨	▨
Regulate	▨	▨	▨						▨	▨	▨	▨	▨
Scan	▨	▨	▨										
Verify	▨	▨	▨	▨	▨	▨							

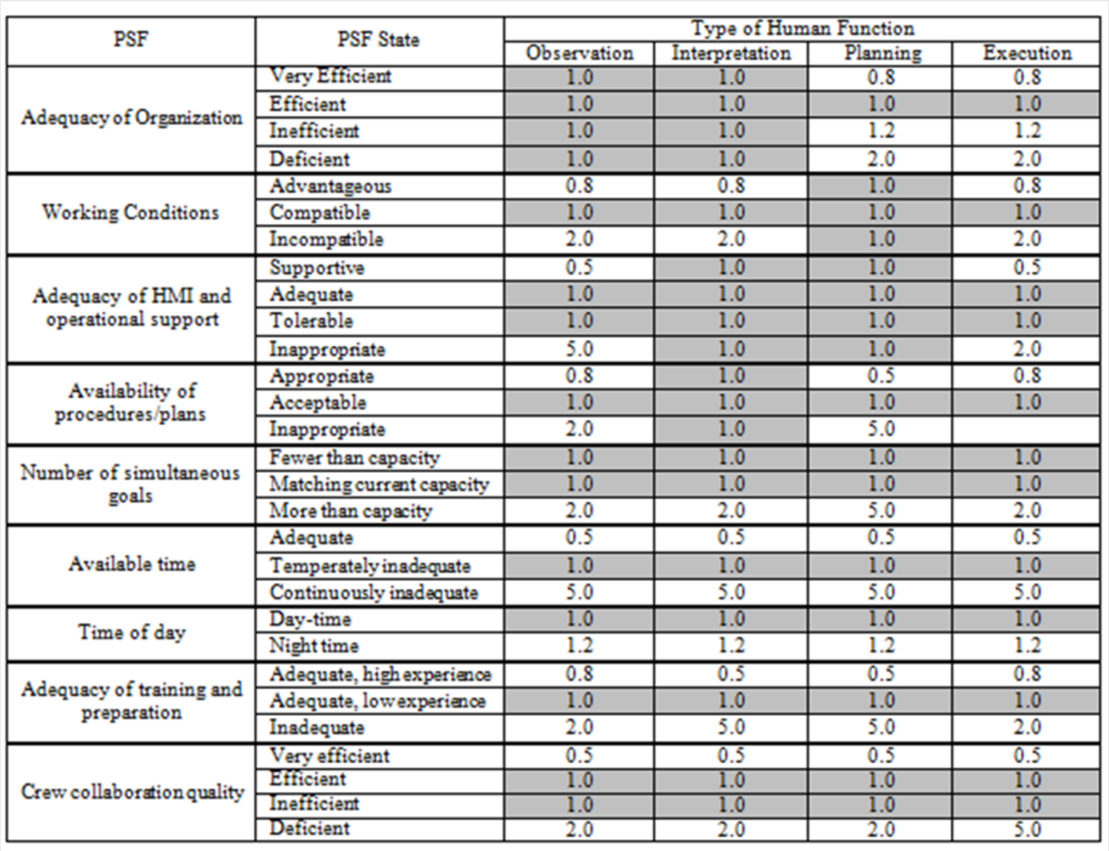
*shaded cells are the possible types of human errors
BHEP: Basic human error probability
O1: Wrong object observed
O2: Wrong identification
O3: Observation not made
I1: Faulty diagnosis
I2: Decision Error
I3: Delayed interpretation
P1: Priority error
P2: Inadequate plan
E1: Action of wrong type
E2: Action at wrong time
E3: Action on wrong object
E4: Action out of sequence
E5: Miss action

Reliability Analysis (HERA) HRA database sponsored by Nuclear Regulatory Commission.

The eight PSFs used in SPAR-H are:

- Available time
- Stress/Stressors
- Complexity
- Experience/Training
- Procedures
- Ergonomics/Human machine interface
- Fitness for duty
- Work processes

Table 2.4: Multipliers for CREAM PSFs



PSF	PSF State	Type of Human Function			
		Observation	Interpretation	Planning	Execution
Adequacy of Organization	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 HMI 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	2.0
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	
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
	Temperately inadequate	1.0	1.0	1.0	1.0
	Continuously inadequate	5.0	5.0	5.0	5.0
Time of day	Day-time	1.0	1.0	1.0	1.0
	Night time	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

The effect of a PSF is a function of the PSF's state, the type of error (i.e., diagnosis or action), and the operation phases in which the task is performed (i.e., at power operation or low power/shutdown operation). The SPAR-H method does not offer an explicit causal model, although a diagram is provided to suggest interdependencies among the various PSFs.

SPAR-H is used to quantify HEPs through the following steps:

1. **Determine the plant operation state and type of activity**. Two distinctive plant states, at-power and low power/shutdown, and two types of activities, diagnosis and action, are modeled. Four HEP worksheets are provided to be used for calculating the HEPs of the following four different combinations:
    - At-power operation and diagnosis activity
    - At-power operation and action activity
    - Low power/shutdown operation and diagnosis activity
    - Low power/shutdown operation and action activity
2. **Evaluate PSF states to determine the multipliers**. Check the states of each PSF on the HEP worksheet. The state of each PSF is associated with an HEP multiplier value (see [24] for specific values).
3. **Calculate HEP using equation provided in the worksheets**. Two equations are provided; the choice of equation depends on the number of negative PSFs. Equation 2.3 is used to calculate the HEP for situations with fewer than 3 negative PSFs. Equation 2.4 is used if there are 3 or more negative PSFs.

$$PSF_{composite} = NHEP \cdot \prod_{1}^{8} S_i \tag{2.3}$$

where S_i is the state of PSF i. For diagnosis tasks $NHEP = 0.01$ and for action tasks $NHEP = 0.001$.

$$HEP = \frac{NHEP \cdot PSF_{composite}}{NHEP \cdot (PSF_{composite} - 1) + 1} \tag{2.4}$$

2.4 Current Problems in HRA

Despite advances in all areas of probability, there is still a great deal of uncertainty about how to best estimate HEPs. This is linked to three problems plaguing HRA: inadequate data collection, inadequate use of data and inadequate modeling. However, these issues are not completely independent. Inadequate data collection limits the effectiveness of models, and inadequate modeling impacts how data is collected. Models are only as good as the data that goes into creating them. Without accurate models, though, HRA lacks the framework to influence how data is collected. The data problem is of primary importance in HRA, yet the field remains trapped in circular logic [30].

Understanding the relationship between the human and the machine is difficult with uncertain data and models limited by the data. In order to develop a new model, it is necessary to examine data collection problems and learn from the limitations of older models.

2.4.1 Data Collection Limitations

Despite the fact that human error is a leading contributor to industrial error, major industrial accidents and near misses are still exceedingly rare. While accident rarity is beneficial to society, it creates difficulty for risk analysts as there is insufficient statistical data available. Several factors contribute to the difficulty of collecting accurate data; data scarcity, availability, uncertainty, and relevance each introduce different limits. Serious human error events are rare, and comprehensive data is not usually collected on near misses; this leads to the problem of data scarcity. Additionally, in many industries data is not readily available to analysts because of security concerns. Limited amounts of data leads to problems with data relevance. Real world data is not available for every incident of interest, so analysts must use simulator data or data from other events or industries. The data that is gathered from these events may be only partially relevant to many research tasks.

Machine performance is relatively easy to observe and measure; determining the time between failures or the number of failures per month is generally straightforward and objective. Measuring human behavior is more subjective and qualitative, and depends heavily on analyst judgment and analysis goals. This results in available data being found in various forms, which limits the amount of data that can be inserted into traditional models.

In different industries there are varying amounts of expert estimates, data from HRA models, and failure/success counts. Each of these forms of data comes with its own set of limitations. Expert data is subjective and varies between experts and across industries. Expert data depends heavily on how it's collected and the goal of the data collection [31]. Expert data also depends on the context in which it's collected; situational factors and group dynamics may influence the decisions of experts. Additionally, human performance data gathering techniques are subjective and may vary among experts and industries. This leads to data specificity and significant problems with level of abstraction.

In addition to modeling uncertainty, experimental data and observed data are limited. Experimental data is often incomplete because there are limited opportunities to gather success/failure counts. These problems are compounded by difficulty defining and counting the number of opportunities for failure - we typically notice an action only there has been a failure, which results in uncertain numbers of successes. Additional problems are introduced by disagreement among experts about the level of abstraction at which data should be gathered.

Simulator studies are also associated with a variety of issues. Simulators may not be an effective measure of actual performance for many reasons. There is difficultly replicating exact event conditions in simulators and tests. There is potential for skewed results because simulator participants may not treat the activity as seriously as a real event. Outside factors that are not controlled for may influence the results, and simulators tend to lack unpredictable events outside of those anticipated in procedures. Additionally, among simulator researchers there is disagreement about the necessary content of the simulator experience and required time on simulator [32, 33].

2.4.2 Modeling Limitations

HRA models are subject to the same limitations as the data that goes into them, plus an additional set of limitations associated with modeling. Theoretical model that are at least partially based on data are limited by the quality of the information used to create them. Models are also limited because of the nature of modeling; models are not exact replicas of the data. Current models are heavily dependent on expert judgment; data is not frequently used to develop and validate models. Lack of overlap between human performance models in different industries results in a more limited pool of data available for creation and validation of HRA models.

Many models treat human behavior as strictly binary: either a success or failure. However, human actions cannot accurately be viewed in binary; people don't always completely fail or completely succeed [34, 35]. Other models treat human behavior as random, neglect to include interdependencies between aspects of human performance, or simply aggregate the effect of many factors without considering importance, observability, or measurability of the factors. Attempts to include dependency results in increasingly complex models that are subsequently more difficult to develop. Additionally, increasingly complex models are being developed as HRA industry shifts from action errors (reduced in past decades due to improving ergonomics) to cognitive errors. These modeling techniques lead to additional limitations as better data is needed to fit complex models. This results in difficulty validating models without additional data.

2.4.3 PSF Limitations

In addition to data and modeling issues that affect the entire field of HRA, there are further limitations specific to the use of PSFs. Currently there is not a "one-size-fits-all" PSF set, nor are most PSFs used in HRA defined specifically enough to ensure consistent interpretation across methods. Since there is no definitive set of PSFs used in HRA, different sets of PSFs are used in different methods. There are few rules governing the creation, definition, and usage of PSF sets.

Additional limitations of the PSFs are discussed in depth in Chapter 3 as justification for the fundamental guidelines introduced in the chapter. The PSF limitations in Chapter 3 are discussed with respect to the available data, but the issues are not unique to the data sources. The HERA database [2] contains elements from a number of HRA methods, and the IDAC model aggregates PSF information from over a dozen HRA methods. The limitations in the observed data are in part due to the limitations of the HRA methods used to build the databases. Problems with PSF interdependencies and PSF usage in HRA methods and models are also discussed in Chapter 3.

2.5 Model-based Approach

The remainder of this dissertation discusses a model-based approach to addressing many of the limitations facing HRA. Results presented through the dissertation were developed as part of the process of building a data-informed causal model of PSF interdependencies.

The HRA field needs a new model because available data is in several different forms and current methods do not integrate this data. A Bayesian model would allow analysts to combine data from several sources. Current methods fail to address explicit dependency in human action data quantitatively. Human actions are complex and are never completely independent. Likewise, human failures are not random, and should not be treated as such in models. This necessitates the study of the dependencies between PSFs and what effect this will have on human reliability models. A causal model can be used identify the multiple causes of an event and to trace the common factors that multiply influence events.

Despite limitations associated with modeling and the data feeding the models, there is still a valid case for creating a model. It is difficult to directly measure cognition and thus it is necessary to use models to represent human mental processing. Models are often used to address these mental processes in relation to different situational contexts. A model is useful because there is limited and indirect data which could be used to inform HEP quantification, and there is very little potential for significant increases in data quantity in the foreseeable future.

Chapter 3

Performance Shaping Factor Hierarchy and Principles

The research plan involved selecting a set of PSFs from an existing HRA method and to use these PSFs in the causal model. However, after working with HERA data coders to understand the HERA framework, it became apparent that HRA needed a set of PSFs developed specifically for use in a causal model. Insights gathered during the event analysis process were used to develop an improved PSF classification. This chapter begins with an overview of the sources of data used in this research and a discussion of the limitations of current data. The second part of the chapter details the data classification process used to develop the final PSF set. The third part of the chapter presents a set of fundamental principles that PSF sets should meet to increase reliable interpretation by different experts. The full PSF hierarchy is explained at the end of this chapter. Definitions of the PSFs in the hierarchy are provided in Chapter 4.

3.1 Data Sources

There were two sources of data used in this research: the Human Events Repository Analysis (HERA) database [2] and worksheets from an application of the Information-Decision-Action (IDA) model [1]. These data sources were selected because they contained detailed information about the factors that influenced single human errors in a risk significant incident at a Nuclear Power Plant (NPP). There are additional databases that gather information about human errors in NPPs (e.g., HFIS [36], H2ERA [37]), but they gather information about the factors that influence all human performance throughout an entire risk-significant scenario rather than single human errors within the scenario. The information provided by such data sources is too high level to be used to develop a model of PSFs affecting a single human error.

3.1.1 Human Event Repository and Analysis (HERA) Database

The Human Events Repository Analysis (HERA) database was developed by the United States Nuclear Regulatory Commission (NRC) and the Idaho National Laboratory (INL). It is the first database designed to collect detailed information about the factors that affect human performance in commercial NPPs. The database contains retrospective analyses of risk significant NPP operating events that contain at least one human error. The information is gathered from Licensee Event Reports (LERs), Inspection Reports (IRs) and Augmented Inspection Team reports (AITs).

All data encoded in the HERA database are coded on two forms: Worksheet A and Worksheet B [38]. Worksheet A contains a detailed time line of sub-events, i.e., the successes and failures of hardware, human tasks and organizational elements. The term *event* is used to describe one entire risk significant incident at a NPP. The entire span of a reportable incident is one event (e.g., one LER would be treated as one event). A *sub-event* is a single human task, equipment actuation or failure, or external state that occurs during an event. Each event is comprised of dozens to hundreds of sub-events.

Worksheet B is completed for tasks involving human failure or success[1]. It contains information about the context of the task and detailed information about what influenced human behavior and how human behavior contributed to the scenario. Human sub-events are classified as either a human success sub-event (HS) or a human failure sub-event(XHE)[2]. A fully coded HERA event contains one Worksheet A and multiple Worksheet B forms; one such event is provided as Appendix A.

The 11 PSFs used in the HERA database were modeled after the PSFs suggested in the NRC's *Good Practices for HRA* [39]. The HERA database expands the PSFs from [39] by including specific "PSF details," which provide additional information about the state of each PSF. There are over 250 PSF details that correspond to positive or negative influences on the human; the entire set of PSFs and PSF details can be found in the sample Worksheet B in Appendix A. During HERA coding, the analyst reviews the list of PSF details and selects the details that are relevant to the sub-event. The analyst uses the PSF details to provide additional

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[1] Worksheet B can be completed for any human sub-event. Analysts make very few inferences about the events, so human performance information coded in Worksheet B is rooted in the data. However, this requires that the data sources must contain sufficient detail to allow a detailed analysis without expert inference.

[2] The goal of this research is to create a model of influences that affect the likelihood of human error. For this reason, the analysis is limited to data points that correspond to human error sub-events (XHE). Analysis of the HS sub-events is a topic for future research.

information about the state of the PSF. The state of the PSF generally corresponds to the state of the PSF details: if mostly positive PSF details are checked, the PSF state is “adequate”; if mostly negative PSF details are checked, the PSF state is “less than adequate” (LTA). If no PSF details are checked for a PSF, the state of the PSF is “nominal” or “indeterminate.”

3.1.2 Information-Decision-Action Model Events

The Information-Decision-Action cognitive model [1, 40] is used to analyze the behavior of NPP operators during abnormal operating conditions. The IDA model separates PSFs into internal and external PSFs. However, the focus of the IDA model is on human cognition, so the external PSF list is not comprehensive. An updated version of the IDA model, IDAC (Information, Decision, and Action in crew Context, [41]), expands the IDA PSFs to include a more comprehensive set of external factors and an expanded map of information flow. The IDAC PSFs and information flow scheme are presented in Figure 3.1.

Four events were analyzed in depth in Mosleh, Smidts, and Shen [42] using the Information-Decision-Action model. The IDA events were suitable to be included with the HERA data because they were broken into sub-events at the same level of abstraction as the HERA events. The 4 IDA events were broken down into 9 human error sub-events (similar to HERA XHEs). Each sub-event contains several data sheets that provide classification information and root cause analysis that includes cognitive factors. The data sheets include information gathered from site visits and operator interviews. Contextual information, provided by Mosleh et al. in the analysis documentation, was used to assign values to external PSFs that were not included in the IDA model.

3.1.3 Relationship between IDAC and HERA PSFs

HERA and IDAC use different PSF sets, so it is necessary to understand how the PSFs from each source relate to the PSFs from the other. The mapping was done based on the definitions for the PSFs provided by each source. In Table 3.1, the IDAC PSFs are mapped onto the HERA PSFs. All 11 HERA PSFs are included in the left hand column. A subset of the IDAC PSFs is included in the right hand column. The IDAC PSFs that are not included in the chart were could not be mapped onto HERA PSFs because HERA does not contain an analogous concept. Most of the PSFs excluded from this chart are internal PSFs that cannot be documented in the data sources used in HERA analyses.

Data from both sources was converted into quantitative form using the same approach. Each negative PSF state was assigned a value of one. A nominal/indeterminate[3] PSF was assigned a value of zero. Positive PSFs states were also assigned a zero value. Of the 158 XHE sub-events analyzed, only one contained a positive PSF state.

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[3] We have treated nominal and indeterminate PSF sets as equivalent, uninformed states. An indeterminate PSF state indicates that the PSF does not deviate from the nominal PSF state.

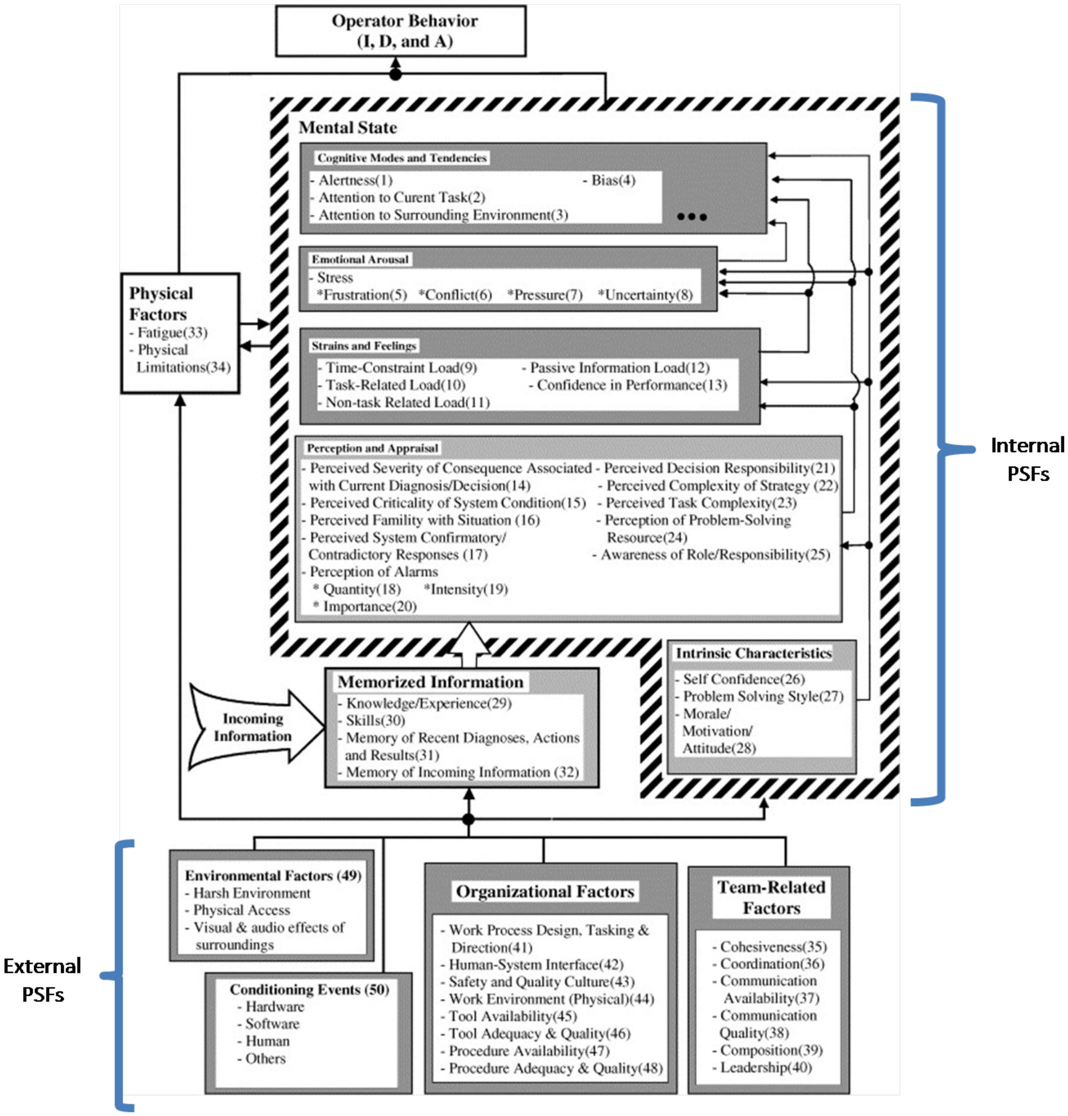

Figure 3.1: The IDAC model provides a logical flow of information from the scenario to the final human performance. The mental state box details the internal cognitive activities involved in interpreting the external information. Information flows from the bottom of the model to the top of the model along the defined paths.

HERA	**IDAC**
Available Time	Time Load; Pressure
Stress/Stressors	Pressure; Conflict; Frustration; Uncertainty
Experience and Training	Knowledge and Experience; Familiarity with situation
Task Complexity	Complexity; Task Load
Ergonomics and HMI	HSI; Environment
Procedures and Documents	Procedure quality, availability; Resources
Fitness for Duty	Fatigue; Abilities
Work Processes	Attention; Memory; Safety Culture; Tool Availability; Bias
Communication	Communication quality; availability
Environment	Environment; Work environment (physical)
Team Dynamics	Team cohesion; Team coordination

Table 3.1: PSFs used in the HERA database (left column) and the IDAC model (right column)

3.1.4 PSF and Data Source Limitations

This section contains insights gathered during the author's experience coding events for HERA. The implications of these insights are presented in data classification and fundamental principals at the end of this chapter.

The HERA database provides raw human performance data in a taxonomy suitable to be used by many HRA methods. It contains detailed information about factors that influenced performance in single human errors. The information in the HERA database is intended to be used by multiple HRA methods. While this is beneficial for the HRA community, it makes analysis difficult because there is no implied structure. During the data-coding process it became apparent that the limitations of current HRA methods were reflected in the HERA database. The lack of structure in HERA, combined with HRA limitations, created several problems, including unintentional dependency, in the data.

The PSFs used in the HERA database were modeled after the PSFs suggested in the NRC's *Good Practices for HRA* [39]. In the HERA database, there are a number of specific PSF details that correspond to each PSF. Further examination of the PSF details reveals that the details were aggregated from several HRA sources (e.g., [24, 43, 36] without reclassifying them into any particular structure. Combining these various PSFs without adding structure resulted in considerable overlap between some of the PSF details within and between categories. One example of this involves supervision. One of the *Work Process* PSF details is "Inadequate supervision / command and control." The same supervisory effect is also detailed in *Team Dynamics* as "Supervisor too involved in tasks, inadequate oversight." For subevents where supervisor participation was inadequate, *Team Dynamics* and *Work Processes* will have a perfect correlation. The presence of this detail in both *Work Processes* and *Teamwork* suggests that the two PSFs have a relationship, but having nearly identical PSF details makes it difficult to quantify this relationship because it obscures the information provided by related-but-different PSF details.

in the HERA database, all of the PSF details were grouped at the same level under a PSF. The lack of structure introduced several additional analysis problems related because PSF details from different methods were designed to capture different amounts of detail. This resulted in partial overlap between PSF details within the same category. This is not problematic on the single PSF level, but this skews analysis when analysis is done at the level of PSF details. One example of this is part of the *Experience and Training* PSF. One PSF detail is "Training LTA," and a second detail is "Simulator Training LTA." Most analysts would consider "Training

LTA" to be a superset including "Simulator Training LTA," but the HERA structure does not make this explicitly clear since both PSF details are listed at the same level. For a sub-event involving simulator training, some HERA analysts might select both "Simulator Training LTA" and "Training LTA," but other analysts might only select "Simulator Training LTA." This inconsistency has the potential to skew analysis of the PSF details.

Another complicating factor is the result of using PSF details from HRA methods that do not differentiate among the multiple causes that can result in the same outcome. Many PSF details do not explicitly differentiate between influences caused by organizational factors, team factors, or person factors. One eExample includes "necessary tools / materials not provided or used." From the machine perspective, it does not matter why the worker used the incorrect tool, but for the identification of the root causes of a failure, the difference between an organization not providing the correct tools and a worker not using the correct tools is crucial. Lumping the provision and use of tools into a single detail limits the ability of the analyst to identify relationships between PSFs on an individual level versus an organizational level. Differentiating between personal factors and organizational factors could offer insight into organizational priorities, personnel training, and safety culture.

Some of the PSF details in HERA that were gathered from HRA methods were actually behaviors, which created difficult for event analysts (see section 3.3.6). Certain PSFs are very difficult to observe, yet most PSF sets lack representation for the visible behaviors that suggest the presence of a PSF. For example complexity cannot be measured directly but characteristics of complex problems, such as ambiguity, can be observed. Some PSF sets blur the line between behaviors and PSFs, or they include behaviors as a PSF, e.g., *Work Processes*. A related problem is the lack of differentiation between PSFs, human failure modes, and human failure mechanisms. The problem here is that person A's failure mode becomes a PSF for person B's error. It is difficult to differentiate between a failure mode, a failure mechanism, and a PSF if the sub-event is not defined carefully.

In addition to some factors being unobservable, other factors are not frequently observed, so they are underrepresented in the data. Two HERA PSFs that are particularly underrepresented in the data are *Environment* and *Fitness for Duty*. The environment in a control room very rarely changes, so there are limited chances to observe control room errors in a degraded environment. With maintenance or balance of plant (BOP), activities the environment may be subject to greater variability, but it is still scarcely observed, in part due to the fact that the environment inside the entire NPP is controlled to some degree (e.g., maintenance workers are generally protected from rain, wind, etc. when working inside of a building). Similarly, HRA experts generally agree that *Fitness for Duty* is a significant contributor to system risk, but it is so rare in practice that it's difficult gather data on; to include it in the model we need to use expert judgment.

Fitness for Duty (FFD) has additional data collection problems because of the connotation of the term. FFD is a loaded term in NPPs; unfit for duty implies that a worker intentionally did something (e.g., came to work intoxicated) to compromise plant safely. However there are many factors that affect a worker's cognitive and physical abilities that are unavoidable consequences of employing human workers (e.g., circadian rhythms, emotions, illness, personal issues).

Additional difficulties were encountered because the definition of "human error" used in HRA is broad. It includes errors committed by single individuals and by groups; in this dissertation these are respectively referred to as"person-errors" and "group-errors." Some of the available data is coded about a single person making an error, but some of the data is a committee made the wrong decision. It is difficult to use such information in the same model.

It is important to note that the HERA database is still under development and event coding continues. While the 25 events in HERA provide a wealth of information about human performance, the number of events is not sufficient to provide conclusive evidence about any relationships between PSFs. Between the IDA and HERA events, there are 158 detailed analysis for human errors (XHEs) among the 29 HERA and IDA events.

The data from these worksheets is dependent within the same event, so theoretically there are only 29 independent data points. With 29, or even 158, data points there is not sufficient data to ensure that each PSF is represented proportionally to its impact on human performance. However, given the possible consequences of human errors in nuclear power plants, it is important to try to learn from any amount of data. The remainder of this dissertation discusses indications of correlation and not necessarily firm relationships. Given the data limitations it is not possible to definitively state that certain PSFs correlate, only that they correlate based on the available data. These correlations must be reinforced with expert information. As events are added to the HERA database over the coming years it will become possible to produce more informed conclusions.

3.2 Data Classification

3.2.1 Approach

None of the PSF sets used by current HRA methods was suitable for use in a causal model because current PSF sets were designed to be assessed by experts, not to be quantified in a model. One of the major issues with many sets was overlap among PSFs. When an expert is assessing the PSFs, the expert can mentally adjust for overlapping definitions. However, in a model it is necessary to either capture this mental adjustment explicitly or to remove the overlap. There were also additional problems with the available PSF sets. Some sets were not comprehensive, i.e., they contained too little information about some external or internal PSFs. Other sets included too many factors that could not be measured; many sets lacks any metrics that should be used to measure the PSFs, and some included specific behaviors as PSFs (e.g., "Work Conduct").

The final PSF set for use in causal modeling was developed by aggregating information from multiple PSF sets and then refining them into a single set that is comprehensive, orthogonal, and measurable. The aggregated PSF information was merged with the expansive list of HERA PSF details and then reorganized into a structured PSF hierarchy.

We selected the IDAC model as the initial framework for reorganizing the data because IDAC offers a hierarchical structure and logical flow of information. Using

IDAC allows us to take advantage of the substantial research done to create the IDAC model. In the IDAC model the PSFs are designed to be defined orthogonally, but not necessarily independent. The IDAC model offers qualitative links between PSFs that can be seen as the beginning of a directed model. The PSFs in HERA lack the logical flow of IDAC, and this logical flow is necessary for the formation of a directed model.

The IDAC model has limitations, though. It was developed to focus specifically on operating crews, so it lacks information relevant to maintenance activities, etc. However, the HERA database provides information about personnel and organizational factors inside and outside of control room operations. The HERA database provides PSF details that can be used to extend the IDAC framework to situations beyond operating crews. Many of the PSFs present in IDAC are rooted deep in human cognition, so they present challenges for data collection. IDAC is also limited in the external PSFs it collects, particularly the organizational factors.

By combining the IDAC structure with the PSF details and observable metrics from HERA we can maximize the use of the data. This is illustrated in the augmented IDAC model in Figure 3.2. HERA provides informative data about human performance plant-wide, but is largely limited to observable PSFs available in documentation. The expanded IDAC structure can be used to introduce influences that are not captured in the HERA data. The resultant augmented model adds information about external influences and observable metrics from data to the cognitive flow provided in the IDAC model.

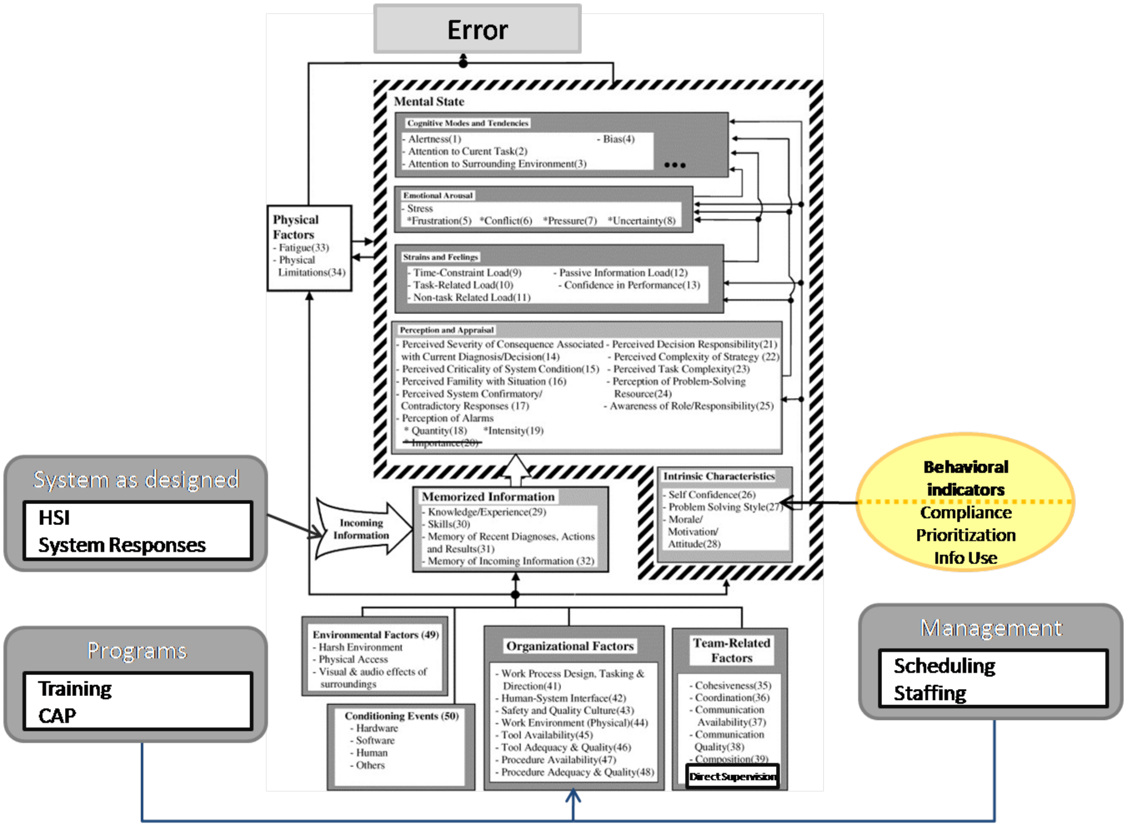

Figure 3.2: The PSF set was developed by integrating additional external PSFs identified by HERA, into the IDAC causal model. Suggested behavioral indicators were added to provide a link between observable metrics and unobservable PSFs that may manifest in behavior.

3.2.2 Process to Develop PSF Hierarchy

Reorganizing the data was an iterative process. We began with the PSF structure provided in HERA, performed analyses, adjusted the structure based on the results, and re-analyzed the data. We repeated this process with each subsequent arrangement of PSFs until a suitable structure was found. Shortcomings in the original HERA database that were identified during event coding were used to impose additional structure on the data for quantitative analysis. The current database does not have observed data about every PSF detail, but by understanding the relationships among PSF details, more information is "learned" from related PSF details. The addition of a hierarchical structure allows us to maximize the use of the data by propagating data through the model.

We approached the mapping with the intention of dividing the PSFs in a way that linked each PSF with a single aspect of the socio-technical system similarly to how they are grouped in THERP[22], with the flow of the IDAC model. The top level of the hierarchy contains six categories: machine-based, person-based, team-based, organization-based, situation-based, and stressor-based. This division ensures that each PSF is defined with respect to a specific aspect of the socio-technical system, which can help identify the root causes of a human error and supports definitional orthogonality.

The categorical division is particularly critical in differentiating between inadequate personnel, team, and organizational influences. The necessity for this division can be most readily seen in the difference between *direct supervision* and *management*. *Direct supervision* represents a direct influence on personnel performance because it comes from the immediate supervisor of the worker. Because of the more frequent and personal interaction with the direct supervisor, it is important to differentiate this from *management*. Management has a more indirect effect on a person's performance because the worker is more removed from management. Management can be seen as intangible, as "the man" passing down orders through a chain of command. The direct supervisor is at the bottom of this chain of command and does not necessarily agree with the management's decisions or emphasize management directions to the worker. In this division, the HERA PSF *Work Processes – Supervision* is separated into distinct entities in both the team-based and organization-based categories.

The six categories overlap with several of the IDAC groups. The *Machine-based* group corresponds to the IDAC *Conditioning Events* category. *Team-based* corresponds to *Team-Related Factors* and *Organization-based* corresponds to *Organizational Factors*. The *Situation-based* group maps onto the IDAC *Environmental Factors* and the *Stressor-based* group replaces the IDAC *Strains and Feelings*. The *Person-based* group encompasses the majority of the remaining IDAC groups.

Development of the hierarchy proceeded in a top-down manner, wherein we organized the data into progressively more specific groups. The aggregated PSFs and HERA PSF details were first assigned to the six high-level PSF categories. The PSF definitions in IDAC were compared to the HERA PSF details, and similar concepts were aggregated into the second level of PSFs. This procedure was repeated for each (second-level) PSF to develop a third layer of PSFs. The hierarchy was then modified based on information gathered during three international HRA workshops at the NRC [44].

Table 3.2 contains the full set of PSFs obtained by dividing the list of PSFs and PSF details among the second and third levels of the hierarchy. This structure is more orthogonally defined than the original HERA structure and is more concrete/observable than the IDAC PSFs. It is reflective of many PSF sets currently used in HRA and of expert information from literature and the NRC workshops.

3.2.2.1 PSF Hierarchy

As can be seen, person-based factors from IDAC are strongly represented in the PSF list. However, this list uses HERA to expand on the IDAC factors, especially in the team and organizational arenas. The IDAC PSFs for *Emotional Arousal* have been redistributed among the *Stressors*. Based on the information provided in the HERA source documents it is very difficult to differentiate between the four types of stress in IDAC. Given that most data gathered in the near future will be retrospective analyses like those in HERA, it is most practical to evaluate situational factors that induce stress instead of attempting to quantify stress. Even simulator events in HERA are unable to differentiate between types of stress due to the unavailability of this kind of information.

HERA provides an excellent medium for eliciting information about team and organizational factors that affect performance. Since the IDAC model was developed to evaluate the performance of a single person, the model does not contain a

Organization-based	Team-based	Person-based	Situation-based	Stressor-based	Machine-based
• Training Program – Availability – Quality • Corrective Action Program – Availability – Quality • Other Programs – Availability – Quality • Safety Culture • Management Activities – Staffing ∗ *Number* ∗ *Qualifications* ∗ *Team composition* – Scheduling ∗ *Prioritization* ∗ *Frequency* • Workplace adequacy • Resources – Procedures ∗ Availability ∗ Quality – Tools ∗ Availability ∗ Quality – Necessary Information ∗ Availability ∗ Quality	• Communication – Availability – Quality • Direct Supervision – Leadership – Team member • Team Coordination • Team Cohesion • Role Awareness	• Attention – To Task – To Surroundings • Physical & Psychological Abilities – Alertness – Fatigue – Impairment – Sensory Limits – Physical attributes – Other • Morale/Motivation/Attitude (MMA) – *Problem Solving Style* – *Information Use* – *Prioritization* ∗ *Conflicting Goals* ∗ *Task Order* – *Compliance* • Knowledge/Experience • Skills • Familiarity with Situation • Bias	• External Environment • Hardware & Software Conditioning Events • Task Load • Time Load • Other Loads – Non-task – Passive Information • Task Complexity – Cognitive – Task Execution	• Perceived Situation: – Severity – Urgency • Perceived Decision: – Responsibility – Impact ∗ Personal ∗ Plant ∗ Society	• HSI – Input – Output • System Responses – *Ambiguity*

Table 3.2: Proposed tiered classification of PSFs for use in HRA causal models. Fully expanded set of PSFs is suitable for qualitative analysis, and the structure can be collapsed for quantitative analysis. The structure also provides a common based framework that can be expanded to deeper levels in the future. Italicized elements are behaviors or metrics associated with the parent PSF.

comprehensive set of organizational PSFs. The combination of HERA and IDAC allows a model that expands on the IDAC PSFs in a focused manner. Alarm-related IDAC PSFs have not been included in the new set of PSFs because the IDAC model is crew-specific and HERA is designed to capture information about all plant personnel. The information captured by alarm-related PSFs in IDAC is captured by the situation-based and stressor-based PSFs in the hierarchy.

Some PSF details could be mapped directly to the IDAC-style PSFs without reading comments. The *Available Time* PSF detail "time pressure to complete task" was mapped directly to *Time-Constraint Load* which is defined in IDAC as "a strain resulting from the feeling of not having sufficient time to solve the problem." The remaining *Available Time* PSF details were mapped onto Task-Related Load because limited time is objective and is based on task characteristics whereas Time-Constraint Load is based on the operator's perception.

Approximately 40% of the PSF details in HERA could potentially be linked to more than one PSF in the new structure. For these PSF details, we analyzed each sub-event comment and assigned individual sub-events to the correct PSF detail. A handful of PSF details were excluded from the mapping because we had no basis for mapping them onto a PSF. These details were so vague or ambiguous that we were unable to link them to any PSF, and they have not been used in any of the HERA events, so there were no event comments that allowed us to better understand the intent of the PSF. For excluded PSF details, we decided that the degree of overlap between many of the PSF details was sufficient to ensure that the intent of the PSF detail was included in the new framework.

The full PSF hierarchy (Table 3.2) is a comprehensive, structured superset of PSFs used in HRA in the nuclear industry. The proposed PSF set in Table 3.2 combines PSF information from most current HRA methods through the PSF details in HERA (gathered from multiple HRA methods), the PSFs identified in the IDAC model (based on literature and analysis of 13 HRA methods), and PSFs identified by the set of international experts during the expert workshop [44]. Table 3.2 also includes elements that are visible behaviors or metrics used to indicate the state of an unobservable PSF; these are indicated in italics in the table. The use of information itself is not a PSF, but it is a measurable indicator of a PSF, *Morale/Motivation/Attitude*. Several other factors are also visible manifestations of underlying PSFs. The list of visible behaviors and metrics is not fully developed, rather it incorporates behaviors explicitly identified in current PSF sets and those identified during the expert workshop [44].

The chart in Appendix B illustrates how PSFs used in current HRA map onto the new PSF hierarchy. The chart links specific PSFs from the *Good Practices for HRA* [39] to individual PSFs in the proposed PSF hierarchy. It also explicitly maps the superset of PSFs identified by the HRA experts [44] onto the new PSF hierarchy. The PSFs in the hierarchy are defined in Chapter 4

3.3 Fundamental Principles

During development of the PSF set it became apparent that the “ideal” PSF set would adhere to several principles. These principles are the result of insights gathered during data coding and the PSF classification process. The principles are presented as guidelines for development of future PSF sets, refinement of current HRA methods, and for expansion of the proposed PSF hierarchy to more detailed levels.

3.3.1 Single Unit of Analysis

While most errors in NPPs are at some level a team-based error, most HRA methods are designed to evaluate errors committed by a single person. In this respect, team-based errors can be broken down into multiple individual "person-errors." For example, one individual may be assigned the task of adjusting the coolant flow rate, but team members work together to make the decision to adjust the coolant flow rate, and they are expected to intervene if an error is committed. Setting the wrong coolant flow rate is then actually two person-errors: the individual mistakenly sets the wrong coolant flow rate, but each team member also errs by not promptly correcting the individual's error.

This treatment of error is consistent with what is done in the available data. In the HERA database, team errors are broken down into two person-errors, as in the following example.

> Licensee Mechanic (LM) #2 incorrectly re-assembled valve 2MS-0093. LM2 stated that he missed critical steps regarding operation of the spindle lifting device because he was focusing ahead to the step which would set the nozzle ring height. ([45], XHE1).

> LM1 failed to identify the missed procedural steps. As the experienced member of the team, he should have recognized the spindle lifting device steps had been missed. ([45], XHE2)

The implication of this unit of analysis is that, for a single sub-event, the team affects the individual's performance. Over a longer period of time the individual will affect the way that the team functions, but when we consider a single moment, the team more strongly influences the individual than vice versa.

The human may be a member of a team, but we should focus sole on errors committed by one person, not errors in team decision making. Teams cannot exist outside of the individual members of the team, so it is not possible to model the team without modeling the individuals. So while each team will have a unique team "personality," it will be more beneficial to HRA to improve models of a single individual before attempting to model the team.

3.3.2 Direct Influences on the Actor

The team can influence the individual through two channels: the direct supervisor or the teamwork. The group interactions are related to the characteristics of each team member, but it is not necessary to know the state of each individual's person-based PSFs to be able to assess the quality of team interactions. So the way that the team members influence an individual is through the team, and therefore we are not interested in the personal factors affecting each team member, only how these personal factors manifest in team interactions.

Teams and organizations are both composed of individuals, and each member of the team and organization has a unique combination of the person-based PSF states. Thus, the factors affecting performance of a team can be seen as the combination of all of the team PSFs plus the individual PSFs of each team member. So the person-based PSFs of each team member have a "trickle up" effect on the team. These influences may trickle back down to affect individual team members, but the magnitude of this effect tends to be small. Figure 3.3 shows how an individual's performance is affected by the overall state of the machine and the organization. These states are the aggregated effect of the performance of other workers however, the personal PSFs affecting these workers have only a limited effect on the individual's performance. The PSFs affecting the other workers become salient when they manifest in a specific failure mechanism, which forms the conditioning event that contributes to an error by a second person. For example, an operator may make an error because the procedure contains an incorrect step. The PSFs that contributed to a procedure writer's error do not affect the operator, only the error made by the procedure writer affects the operator.

The direct supervisor has a different influence on the individual than other team members. The direct supervisor holds a dual role as a team member and a leader, but we are only concerned with the supervisor's PSFs that affect the individual that we are analyzing. As a leader, the direct supervisor provides instructions and directions to the team members. As a team member, the direct supervisor works together with the other members to complete tasks, but not necessarily in a supervisory capacity. Therefore some of the person-based factors of the direct

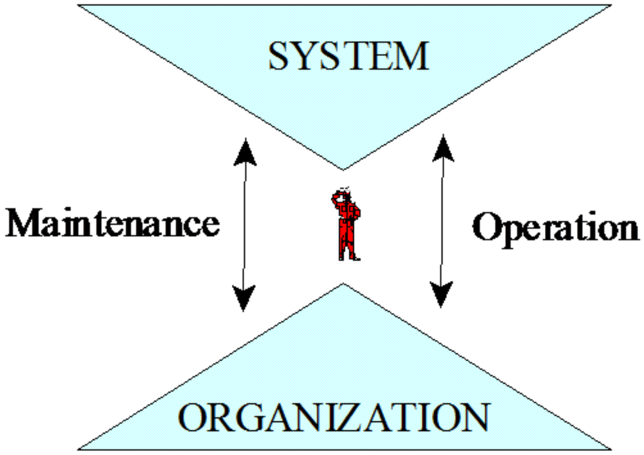

Figure 3.3: The PSFs included in an analysis must directly influence the individual's behavior. PSFs that influence the behavior of other workers form the system and organizational contexts for the individual's behavior. [46]

supervisor may affect the individual team member through leadership and personal interactions. Characteristics of the supervisor such as fatigue will affect the way the supervisor interacts with an individual, but we're only interested in how these interactions affect the person; therefore we're not interested in the fatigue PSF, only in the supervisor's behavior (i.e., the leadership PSF) as it directly affects the behavior of the individual. Likewise, the personal characteristics of members of management will not directly affect the performer, but certain behaviors exhibited by the managers may affect the worker. Therefore management behaviors are included as part of the organizational PSFs, while management attention, etc. are not.

When evaluating the state of PSFs contributing to an error, it is necessary to focus on the period of time immediately around the error. It is necessary to consider what inputs the actor receives and if the actor would act differently if the inputs were changed. In the case of a broken pump, it is highly likely that the operator would have committed the same error regardless of the cause of the broken pump. If we extend the analysis to include the causes of previous errors, we will collect too much information that is unrelated to the performance of the actor. The size of the analysis will snowball if each error includes the PSFs that affected the every previous human error. By including the causes of previous errors we collect too much information that is unrelated to the performance of the actor. We need to avoid collecting information that does not directly influence the error we are evaluating. The PSFs that contribute to an error are generally not included in subsequent sub-events since they manifest in the context of these subsequent sub-events.

3.3.3 Consistent Sub-event Parsing

The division of events into sub-events for analysis is critical for understanding the relationship between the PSFs. Consistent sub-event parsing is necessary to ensure that the PSF information collected is at the same level of abstraction. It would not be helpful to compare every PSF that influenced the performance of workers throughout the duration of a reported accident event with the PSFs that influenced the behavior of a maintenance worker who selected the wrong type of screwdriver.

One of the big issues in HRA data collection is related to sub-event parsing, or the selection and application of task analysis rules. One of the greatest difficulties in task analysis deciding where to stop. The lack of a systematic procedure for determining when to stop creates many issues in HRA. There is much disagreement among experts about stopping, and this leads to different data sets being broken down to different levels of abstraction. Current task analysis techniques often use one of four stopping rules [47]:

1. The causal path can no longer be followed due to missing information;
2. A familiar cause is found to explain the path;
3. A cure is available;
4. Responsibility can be allocated to a person.

Selection of a stopping rule is based on analyst preference, the purpose of the analysis, and the context. These stopping rules present issues about nature of error/control and where to place blame.

The events in HERA are parsed into sub-events based on 4 questions:

- **Actor** - Is there a different person/crew performing the action?
- **Goal** - Is there a different goal for this action?
- **Means** - Does this action use different equipment, a different task, or a different system?
- **Outcome** - Are there different consequences for the actions?

Thus, tasks such as turning a dial are typically not considered since it is a part of the goal "set the coolant flow rate." The sub-event breakdown of an entire event can be found in the event time line (Worksheet A, Section 4) in Appendix A. The analyses described in the remainder of this dissertation rely on events that are parsed into sub-events using these four rules. Additional data points included in this analysis must follow the same sub-event parsing rules, but the greater implication for HRA is that data for any purpose must be parsed in a consistent way.

Additional event parsing guidance for HERA is provided in [48]. Generic guidance for task analysis in HRA can be found in [47].

3.3.4 Definitional Orthogonality for PSFs

Current PSF sets are not suitable for construction of a causal model due to overlap between PSFs within the same set. This overlap is due in part to inherent dependency and interaction between the PSFs, but the overlap also exists because the PSFs are not uniquely defined. In order to gain better understanding of the inherent dependencies and interactions among the PSFs it is necessary to ensure that the PSFs are separately defined entities, i.e., that they are orthogonal[4].

Definitional orthogonality should not be confused with independence; the difference between them is significant. Independence is something that can be observed in quantitative analysis, whereas definitional orthogonality is a qualitative assessment of the way the PSFs are defined. Definitional orthogonality implies that the factors do not overlap in their definitions, and therefore each PSF observation can be clearly and consistently placed into a single category. However, these categories can still influence each other. Independence implies that the factors do not overlap

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[4] When discussing PSFs the term *orthogonal* refers to how the PSFs are defined. It should not be confused with mathematical orthogonality.

and also do not interact with each other. Model elements must be orthogonally defined to remove overlap between the definitions of the elements and thus focus on how the elements interact instead of overlap.

Overlapping PSFs introduce error into the calculations because some elements are double-counted. This leads to over-estimation of the influence of certain PSFs and also skews the relationship between the PSFs. This skewed relationship masks the way the elements interact together to produce different influences. Thus, to properly capture the relationships among PSFs, each PSF must be defined orthogonally. This also ensures consistent interpretation of PSFs among experts.

3.3.5 Value Neutrality

The *Good Practices for HRA* NUREG suggests that the PSFs are to be measured on a scale from weak to strong representing either a positive or negative influence on the situation. In the HERA structure, the PSFs are sorted into separate sections for positive influences and negative influences. However the structure is not parallel – there are fewer positive PSF details than negative details, which gives the database a negative slant.

One way to eliminate this inequality is to use PSFs that are value neutral. The value neutral PSFs will ensure that there is an equal opportunity for PSFs to be selected as positive or negative. It will also allow future analyses to replace the binary scale used to evaluate PSFs with additional levels of discretization or even a continuous distribution of the influence.

Value neutral PSFs are defined in such a way that the each PSF could be checked as either positive or negative depending on the situation. The same PSF may change from a negative influence to a positive influence based on the context of the scenario, and it is difficult to capture this with a biased set of PSFs. PSF details such as "Procedures Less than Adequate" can be made value neutral by restating the detail as "Procedure Adequacy," which allows the analyst to indicate a positive or a negative influence.

3.3.6 PSF Metrics and Behavioral Indicators

One of the shortcomings of many HRA methods is the lack of differentiation between factors that shape performance and behaviors that indicate the state of these factors. Many HRA methods include a "Work Conduct" or "Work Practices" PSF, which often contains a behavior that indicates the state of an internal (cognitive) PSF rather than the true state of the PSF.

The HERA framework was designed to capture exclusively PSFs, not behavioral indicators of the PSFs. However, several behaviors are included in the list of PSF details in HERA, but they are interpreted in a manner consistent with capturing only PSFs and not behaviors. For example, based on current coding guidelines, the PSF detail "Procedural adherence LTA" would only be marked in an error sub-event if a previous sub-event contained non-compliance.

To clarify, assuming the following hypothetical operations situation. Sub-event 1: A maintenance worker skips a procedure step and fails to reconnect a temperature sensor to the display. Sub-event 2: Operator notice that the temperature is out of the normal range and (incorrectly) disables a system without looking at back-up sensors.

"Procedural adherence LTA" would *not* be indicated for the first sub-event because improper adherence to the procedure is a behavior exhibited by the maintenance worker. "Procedural adherence LTA" *would* be indicated for the performance of the operator, though, because maintenance worker's behavior caused the broken sensor, which contributed the operator's error. For the operator, it does not really matter why or how the maintenance worker erred, because all the operator registers is a conditioning event: "I have 2 conflicting sensors." The reason that the pump is broken is of no consequence to the operator and also does not provide additional information for the HRA analyst. However, the behavior "Procedural adherence LTA" is relevant to understanding the PSFs underlying the performance of the maintenance worker. It could be an indicator of LTA personal morale/motivation/attitude, which is otherwise unobservable.

PSFs can be completely observable, partially observable, or unobservable. *Tool Availability* can be observed by anyone: either there is a screwdriver on the table or there is not a screwdriver on the table. in contrast, we cannot observe how an individual views the level of complexity of a situation because we cannot directly measure their knowledge. However, we can partially observe complexity through the number of tasks that the person is assigned. The level of complexity can be assessed from consideration of the observable number of tasks and from the person's performance on an IQ test. For retrospective analysis it is nearly impossible to assess the Morale/Motivation/Attitude of a worker without citing the behaviors that are used to indicate these internal states. We cannot observe the importance a person places on safety, but we can observe how the person complies with safety rules. Compliance is an observable metric used to assess the attitude toward safety.

The use of information itself is not a PSF, but it is a measurable indicator of morale, motivation, and attitude. Several other factors are also visible manifestations of underlying PSFs. There are many PSFs that cannot be directly measured, but it is possible to measure certain metrics that indicate the state of an unobservable PSF. PSF sets should be explicitly associated with behaviors that are not actually Performance Shaping Factors, but are visible metrics that indicate the state of the underlying PSF. See [46] for discussion of additional metrics and behaviors that can be used to assess the state of PSFs.

3.3.7 Summary of Fundamental Properties of PSF Sets

- HRA methods must clearly define their unit of analysis (person versus team). Given the current state of HRA, analysts should focus on improving factors that influence the performance of a single persons before attempting to model the team as a whole.
- Analysis should consider only those PSFs that directly impact the individual's performance. PSFs that contribute to the failure modes of other workers do not affect the individual; the only effect is through the failure.
- Events must be parsed into sub-events consistently based on established rules.

- PSFs must be defined orthogonally, i.e., they must be separately defined entities.
- PSFs should be value neutral to leave room to expand the way they are measured, e.g., “ Adequacy of Procedures” vs “Procedures Less Than Adequate.”
- PSF sets should include behaviors and metrics that are visible indicators of invisible PSFs.

Chapter 4

Definitions of Proposed Performance Shaping Factors

The PSF hierarchy introduced in section 3.2.2.1 was created to provide a structured way to combine PSFs as necessary to for different types of analysis. The PSF set has been developed to be suitable for both quantitative and qualitative HRA applications. All of the PSFs on the hierarchical list of PSFs presented in this section may not be possible to include in quantitative analysis. The hierarchy provides flexibility to use the same set of PSFs for different applications; it can be used for computer modeling which requires every factor to be explicitly identified, and also for manual error analysis and HEP calculations as in many HRA methods.

The combination of the IDAC structure, the HERA PSF details, and information from expert workshops has resulted in a detailed, structured set of PSFs for use in HRA. The PSFs reflect the orthogonal structure of PSFs in IDAC which reduces overlap between the PSFs while still permitting natural dependencies to be included. The PSFs in the hierarchy are reflective of many PSF sets currently used in HRA and of expert information from literature and the NRC workshops.

During analysis of the HERA data it became apparent that teamwork and organizational factors were at the root of many of the human errors. However, not all human errors were organizationally based. For this reason the Work Processes PSF has been broken down into organizational and personal components.

Humans are a part of teams, which are part of organizations. Organizational culture exists outside of each human, but each human also exists outside the organization. Safety culture cannot fully account for the behavior of every member of the organization because each person retains free will and personal work practices. However, there is an influence of the organizational culture on the human work practices, and human work practices may also influence organizational culture.

One of the shortcomings of the Good Practices PSFs (see [39], B is the blurring of the line between individual and organization. The new set of PSFs contains Work Practice elements that parallel each other in the organizational and human sections. Both humans and organizations can display poor work behaviors, but they are not necessarily related. In most cases safety culture will influence both sets of work processes, but in the end the human and the organization must each be held responsible for their behaviors. Differentiating between organizational and personnel work conduct will allow HRA analysts to better address the source of problems.

Specific behaviors associated with work processes have been explicitly linked to the set of PSFs. The behaviors themselves are not PSFs, but they are visible manifestations of an invisible PSF. Standard HRA methods do not differentiate between the behaviors that demonstrate proper or improper work practices.

Knowledge, Experience, and Training is one PSF in HERA. We have separated this into two PSFs, one for training and one for experience or other knowledge. The *Training* PSF represents the specific knowledge that is expected to be taught to workers by the utility. The *Knowledge and Experience* PSF includes the basic knowledge one can be expected to possess before being hired at an NPP. It also includes the skill of the craft knowledge obtained through time in one's profession. In post-event analyses it is difficult to differentiate between lack of knowledge and lack of knowledge due to training. In the HERA analysis the source documents are interpreted at face value and no assumption is made about training unless training is specifically mentioned.

The PSF framework proposed is organized with respect to which aspect of the system is responsible for the PSF, i.e., the root cause or a place in the system where defenses could be built. Most PRA models are intended to identify and correct problems before they negatively affect the plant. An inadequate procedure may be the direct cause of an operator error, but procedures are maintained by the organization, so the procedural inadequacy is the "fault" of the organization.

The PSFs presented each have 2 different facets: the objective aspects of the scenario and the perceived aspects of the scenario. The objective view is the outsider view of the situation. This is what we capture in HERA now, based on expert opinion. The perceived view is the workers view of the situation (which is not necessarily correct). Simulator experiments are currently the best way to gather data that includes worker perception since analysts can interview operators. However, in post-event analysis it is very difficult to differentiate between the perceived conditions and the real conditions. The use of simulators could enable analysts to differentiate between perceived and real conditions, but current HRA models are not equipped to evaluate them differently. The framework provided here is designed with both current and future uses in mind. Future data-collection efforts should separate perceptions from realities to enable future models to capture these relationships; the models presented in this dissertation will assume that there is no difference between perception and reality.

4.1 Organization-based Factors

The organization-based PSFs refer to the factors that are defined by or are under the control of the organization. In the span of a single operational event, these factors are generally static, but they are likely to change over a longer period of time (e.g., several months or years). The organization-based PSFs include the organization's attitudes and certain organizational behaviors that influence the performance of workers. Safety culture and management have a wide impact on all plant personnel. Management behaviors such as scheduling and staffing shape personnel performance because they are directly related to the number and type of tasks assigned to workers, the composition of work teams and the qualifications of personnel. The organization-based PSFs differ from the machine-based PSFs because the organization has primary responsibility for these factors. HSI is machine-based because it is a static system that is designed and constructed once and is unlikely to change significantly throughout the life of the plant. In contrast, procedures can be updated relatively easily and frequently by the organization.

The resources PSF includes the procedures and tools provided by the organization. It also includes other information resources that should be provided to personnel. This can include maintenance records and databases, log books, etc. While the specific part of the organization that is responsible for the various resources may change, the impact on behavior is that the necessary tools and information are not provided to the worker. On a broad level, the organizational programs can also be seen as organizational resources. The programs-based PSFs include the non-physical resources provided through training programs in addition to other plant programs not identified in the data sources.

4.1.1 Training Program

Utilities must ensure that personnel have the correct knowledge to perform their jobs successfully and safely. One part of the utility job is to ensure that personnel have important aptitude and skills before being hired (i.e., proper staffing), and the utility must also continuously train employees to ensure that their knowledge and skills are up to date and relevant.

Training refers to the knowledge and experience imparted to the personnel by the utility. Training includes the content of training courses, the scheduling of training courses, and the frequency of training. Personnel must be trained on how to properly use necessary tools and must be prepared to deal with emergency situations. Training must contain correct information and must be broad enough to provide personnel with the knowledge to deal with dynamic problem situations. Training differs specifically from knowledge in that the same training is provided to all crews and crew members, but the information retained from training may differ. This retained information is where training becomes knowledge, and this knowledge is different for every crew member.

In some HERA events it is impossible to determine why there was a lack of knowledge, only that the person did not possess the necessary knowledge for the task. These cases are not labeled as training issues - they are knowledge issues. However, in certain cases it is explicitly stated that training led to the knowledge problem, in which case training issues are indicated. Because of the close relationship between training and knowledge, they are linked in the model with training contributing to knowledge, but leaving room for other influencing factors as well. Examples of LTA *Training* are:

- The simulator's high pressure steam dump system model did not match the actual plant response: HPSD system response in the simulator was ten times slower than in the plant.([49], XHE12)
- Construction personnel had not received training on fire fighting or emergency procedures (including training on when to initiate a fire alarm). ([50], XHE23)

4.1.2 Corrective Action Program

The *Corrective Action Program (CAP)* is the organizational approach to correcting known deficiencies. The CAP covers the organization's willingness to fix problems, including the priority it places on problems and the compliance with regulatory requirements [14]. The CAP PSF encompasses the quality of the CAP, root cause development, and also how the organization deals with personnel who raise concerns. The CAP is related to the organization's safety culture; organizations with poor safety culture will not place the same emphasis on correcting problems as would organizations with positive safety culture. The CAP is also related to the human-based *Compliance* behavior; CAP is the organizational equivalent of human work practices related to detecting and resolving problems.

In many HRA methods, the CAP is part of the broad work processes PSF. Examples of Less Than Adequate (LTA) *Corrective Action Program* include:

- While maintenance personnel corrected set points in previous installation, no action was taken to ensure that the mistake was not repeated. ([51], XHE3)
- Management was aware of continuing problems with CTG 11-1. CTG 11-1 had been overhauled in 1996, underwent major maintenance in 1997; After 1999 CTG 11-1 failed maintenance performance criteria of less than 3 failures in 20 demands. 14 failures related to CTG 11-1 were observed between December 2000 and the time of this event. Management was aware of continuing problems with CTG 11-1 but did not establish interim corrective actions to ensure that unit started on demand. ([51], XHE1)
- Corrective actions were focused on addressing the symptoms and maintaining operability rather than identifying and correcting the source of the problem.([52], XHE30)

4.1.3 Other Programs

We recognize that the Training and corrective Action Programs are not the only programs that impact human error probabilities. The *Other Programs* PSF is included to acknowledge this and to ensure completeness in the second level of the hierarchy. Additional programs can be added to the hierarchy here.

4.1.4 Safety Culture

Safety Culture (safety climate [53]) characterizes the organizational attitude, values, and beliefs toward worker and public safety [12, 19]. According to the IAEA, 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 [54].

The safety culture is typically set by management and trickles down through the ranks to affect performance at all levels. An organization with a positive safety culture takes effort to maintain safety even when it might adversely impact productivity or profits. Different organizations and even groups within organizations, have different priorities with regard to safety and productivity [15]. In a NPP, safety culture encompasses the quality assurance of equipment, etc. [10].

Safety culture is at the root of many system-wide failures. Less than adequate safety culture is frequently observed in the data simultaneously with LTA states of other organizational elements in sub-events. Safety culture cannot be independent of any aspect of performance and thus its effect propagates through the model.

Safety culture itself is not inherently observable. However, we can observe ways in which safety culture is implemented. The safety policies [15], the way management prioritizes tasks, and the way workers comply with procedures are more visible elements that can be linked to safety culture. Examples from the data include:

- Management routinely exceeded the recommended time between preventative maintenance tasks. ([51], XHE1)
- Management favored production over safety. There was immense pressure on production, so concerns were analyzed away and postponed. ([52], XHE18)

4.1.5 Management Activities

Management is defined as the personnel at the upper layers of the organization. The management is not expected to communicate frequently with the people responsible for performing daily maintenance and operations duties. Management can be interpreted as an abstract authority, "the man" that leads a group or organization without being directly involved in all aspects of day-to-day operations. It is the management that sets expectations for the plant, oversees hiring, and most strongly influences safety culture throughout the plant. There can be several layers of management within a single plant or utility. In this framework the definition of management is relative to the person performing the action. Management must be at least one layer removed from the actor and does not frequently interact with the actor.

An example of LTA management is:

> Management was aware of continuing problems with CTG 11-1 but did not establish interim corrective actions to ensure that unit started on demand. ([51], XHE1)

In this example, the operational staff is not responsible for ensuring that the equipment works properly. The maintenance staff are not responsible for scheduling corrective actions – this requires coordination between departments and is handled at the management level; therefore this is a management failure.

Staffing and *Scheduling* are two aspects of *Management*. They are both management behaviors, but they act as PSFs for individuals throughout the plant.

4.1.5.1 Staffing

Staffing refers to the way that the organization hires and assigns tasks to personnel [15, 55]. It is an organizational responsibility to ensure that the personnel they hire have the knowledge necessary to perform their jobs. It's also an organizational responsibility to assign appropriate numbers personnel to tasks, to ensure that teams have members with complimentary skills, and to ensure that teams have had appropriate opportunities to train together [12, 56]. Staffing must balance the organization's interest in keeping costs low, preventing errors, and ensuring that they have a continuous workforce (e.g., training new workers before experienced workers reach retirement). This requires consideration of the number of experts versus inexperienced staff that are placed on a task.

Staffing issues can impact personnel performance in several ways. LTA *Staffing* may cause personnel to be assigned too many tasks, certain staff to carry the majority of the task load, or personnel to work without sufficient rest time between shifts. Staffing can also include team issues wherein the organization rearranges crews without giving them ample opportunity to train together before being placed in operating situations. Staffing also considers inappropriate hiring decisions that result in personnel without the necessary skills being assigned unfamiliar tasks. Examples of LTA *Staffing* include:

- Both [plant] units were faced with a backlog of maintenance tasks which suggests that they needed additional staff. Task was likely a low priority task due to overwhelming number of tasks for maintenance staff. ([57], XHE3)
- This particular crew had trained together only on startup activities. The crew had attended a teamwork building session, but not all as members of this crew. This staffing arrangement affected crew communications, teamwork, and stress during this event. Previous training had not established consistent procedure usage for stopping a cooldown under the event conditions. ([58], XHE4)

4.1.5.2 Task Scheduling

Task Scheduling refers to how the organization plans and distributes tasks to personnel. Task scheduling encompasses activity planning and scheduling [10, 12, 15], resource allocation [14], and ordering (prioritization) of planned tasks [11]. Task prioritization by the organization should not be confused with the personal *Prioritization* behavior of individual workers. The organizational prioritization problems occur over a longer time scale and multiple people are involved in the planning and decision making directly or through a review process. Personal prioritization problems usually occur over a shorter time period (e.g., during an emergency situation) and involve a single individual making the decision. Organizational *Task Scheduling* is most salient for maintenance work because typically maintenance work can be planned unlike operational emergency tasks.

Task scheduling can be related to staffing issues, including cases where inadequate number of staff is available to complete tasks, so tasks cannot be completed in expected time. In the HERA database task scheduling can be indicated as frequent task rescheduling, inadequate scheduling of test and surveillance activities, or assigning too many tasks to an employee or team. In the latter case, there is a strong relationship between *Task Scheduling* and *Staffing*. While *Staffing* and *Task Scheduling* do not have a direct causal relationship, the high correlation between the two can be explained because the same management influences both PSFs. Scheduling also includes the way the organization prioritizes tasks, such as in HERA event [59]. Examples include:

- Plant owners delayed repairs to TSC DG system; information suggests that this was deprioritized due to overwhelming number of repairs necessary at IP2 and IP3. ([59], XHE2)
- Fermi has a policy that allows preventative maintenance to be performed up

> to 25% later than recommended time. Scheduling of preventative maintenance was inadequate. ([51], XHE1)

4.1.6 Workplace Adequacy

Workplace Adequacy refers to aspects of the plant environment that can be changed by the organization. This includes aspects of workplace layout [10], environmental stress [60] and workplace configuration [14]. In the HERA database this is captured as a Conduct of Work PSF detail "Housekeeping LTA". *Workplace Adequacy* generally refers to the quality of the office environment and thus differs from HSI, which refers to fixed plant equipment. An organization cannot change the dimensions of an access panel (HSI) or the weather (work environment), but the organization can control where procedures are stored and when broken light bulbs are changed. If workers feel that the necessary tools or procedures are too far away, or if tools are locked in a cabinet that can only be accessed by a supervisor, workers are more likely to use workarounds that could result in error.

An example of LTA *Workplace Adequacy* is:

> RO reported difficulty reading procedures due to insufficient lighting. Light bulbs had not been replaced in available reading lamps. (Hypothetical example)

4.1.7 Problem Solving Resources

The *Problem Solving Resources* PSF is a factor that consists of the necessary procedures, tools, and information required to perform a task. Operators and maintenance personnel are typically limited to use the resources at hand to complete tasks. Problem Solving Resources is a generic category that includes the different types of resources necessary to successfully perform most tasks in an NPP.

4.1.7.1 Procedures

Personnel actions are often prescribed in a set of *Procedures.* This leads us to consider two PSFs relating to the available procedures: *Procedure Quality* and *Procedure Availability.* Procedures are explicit, step-by-step instructions for performing a task. Personnel are instructed to follow procedures without deviation. Hypothetically there should be no error made if the procedures are followed to the letter. However, procedures are often imperfect and can lead staff to make errors. LTA *Procedure Quality* can be broadly defined as any condition where a procedure exists but is insufficient to ensure that the job is completed correctly. This could include procedures that are vague, wordy, or incorrect as well as procedures that are poorly written, organized, or formatted [11, 15, 61]. LTA *Procedure Availability* is the situation where procedures for the task at hand do not exist or are not accessible. This could include unanticipated conditions or conditions where a procedure is only partially relevant because different conditions exist.

An example of insufficient procedures contributing to error is:

> Preventative maintenance procedures for the fuel oil pump did not require personnel to check the arcing horn clearances. Also did not state clearance dimensions required for arcing horn. ([51], XHE4).

An example of incorrect procedures contributing to error is:

> Adherence to modification process during installation (XHE1) resulted in inappropriate set points remaining in CECO [A plant-specific maintenance database]. ([51], XHE3)

Both of these elements feed the *Procedures* PSF because ultimately they have a similar effect: personnel do not know what to do next, or personnel do not realize that they should do something. Given the amount of data currently available, we cannot do quantitative analysis at the quality vs. availability level for procedures and it is necessary to lump them together as *Procedures* to maximize data.

4.1.7.2 Tools

Tool Availability and *Tool Quality* refer to the physical tools provided to workers by the organization. Proper tools (including number and type) must be available to ensure that personnel do not have to develop work-arounds or postpone tasks due to LTA tools. For previously scheduled tasks (e.g., preventative maintenance), tools must be made available when needed; that is, management should not schedule simultaneous tasks that involve the use of the same limited quantity tools. Tools must also be in working order, including proper calibration [11, 15, 22, 61].

As digital systems become increasingly common the tool availability category can be used to include the availability of software systems (e.g., maintenance databases). This category does not include lack of information necessary to make decisions, only the tools necessary to implement actions. HSI is not a tool; tools are not a fixed part of the system and are generally more portable than HSI.

Tool availability does not refer to cases when the correct tool is available but an incorrect tool has been selected, because this is an individual knowledge or work practice problem. Likewise, poorly designed HSI or lack of necessary information are not tool problem; these are problem solving resource issues, but they are not tools. Examples include:

> The licensee only had enough tools to drain one TDAFW at a time, which forced them to decide which unit to work on first. ([62], XHE0.11)

4.1.7.3 Necessary Information

Information Availability and *Information Quality* refer to necessary information about the system or task that is pertinent to the work. Information can include log books from previous shifts, vendor manuals for parts, HSI output, or communication with other personnel. The *Information Availability* and *Information Quality* is intended to capture information that is exclusive of the procedures or tools.

This PSF indicates only that there was missing information given to the personnel. The reasons for the missing information, be it lack of communication or missing vendor manuals, are captured in other PSFs. For example, this category does not necessarily capture all malfunctioning parts of HSI, but it does include cases where malfunctioning HSI makes it impossible to obtain necessary information; in this case both *HSI* and *Information Availability* would be LTA and thus there is a causal relationship between them in the model. As a PSF, *Information Availability* captures the impact of malfunctioning HSI – if the HSI is malfunctioning, but the information is not necessary, then the broken HSI has no impact. It is the lack of information from the HSI that causes problems, and thus HSI is a factor that influences the availability of information, which in turn influences human performance. One example of LTA information is:

> CECO [maintenance database] information had not been updated to contain proper low voltage trip set points for CTG. ([51], XHE3)

4.2 Team-based Factors

A team can be described as any group of people expected to work together to complete a task. In the plant context, team members are expected to interact directly either in person or in writing. Members of the same operating crew or the same maintenance shift are certainly a team, but members of different operating crews can also be considered a team because the offgoing crew is expected to pass certain information to the oncoming crew. The defining characteristic of the team is that people work together to achieve a common goal.

4.2.1 Communication

Communication refers to the ability of team members to pass information to each other. Communication can be verbal or in writing, but it does not refer to the ability of the human to interact with the machine. Communication allows team members to have knowledge of a shared situation [63].

Communication is broken down into *Communication Availability* and *Communication Quality*. Complete lack of communication is LTA availability – there was no information passed. With LTA quality of information, some information is passed, but it may be partial information or incorrect information. Untimely communication has the same effect as lack of communication – the information is not communicated when necessary. While LTA quality versus LTA availability of communication may have a slightly different effect on behavior, for the purposes of this model we treat the two together as "Communication LTA" because in many cases partial information, like no information, is still insufficient to perform the correct actions.

Communication is related to the *Information Availability* PSF. The availability of information could be directly caused by LTA communication, but other organizational factors could cause correlation between the two. One such example is a case where poor safety culture allows portions of the HSI to remain broken thus denying operators necessary information. In this case communication does not directly affect the availability of information, but the poor safety culture likely also affects communication. Likewise, communication does not always cause lack of information. Poorly communicated information may not impact the scenario if the information does not alter human performance. Examples include:

- Set points were previously corrected (HS1), but this information never reached the CECO database. ([51], XHE3)
- The off-going crew failed to communicate the status of the ESW system to the

> oncoming crew; this would have highlighted the importance of the alignment. ([64], XHE13)

4.2.2 Direct Supervision

Direct Supervision serves as the link between management and the team members. In literature, direct supervision and management are collectively referred to as leadership [15, 55, 56]. In the new framework, *Direct Supervision* has been separated from *Management* because direct supervisors work with and assign tasks to personnel. The direct supervisor can be seen as a member of the team, albeit a member with additional authority and responsibility. The supervisor sets a direction for the team and influences the attitudes of the team members [18]. The supervisor has the dual responsibility of setting goals for the group and also working with group members to accomplish these goals [65]. In the HERA database information is collected on inadequate supervision, either in the form of not enough direction or a supervisor being overly involved in tasks as in the following example:

> The SNSS was too involved in trying to restore CW pumps to be able to maintain his oversight and advisory roles. ([66], XHE12)

4.2.3 Team Coordination

Team Coordination refers to the overall interactions of the team, including division of responsibilities and ability to work as a unit (teamwork) [15, 17, 12]. *Communication* and *Direct Supervision* are aspects of *Team Coordination*, but *Team*

Coordination also goes farther and considers additional factors that contribute to overall team performance. This includes planning and scheduling on the team level and decisions made during team meetings. While poor communication could be responsible for the poor coordination, there are additional factors that could lead to poor coordination such as a lack of knowledge in the team or poor team interactions wherein one member dominates the conversation or other members are unwilling to speak up. In the HERA database team coordination is captured in context of the adequacy of team interactions. One example is:

> The relief-crew supervising operator failed to recognize that the reactor operator who reported the decrease in the Train B ESWS bay level was plant qualified and had the ability to recognize the level drop and appropriately understand the safety significance. ([64], XHE14)

4.2.4 Team Cohesion

Team Cohesion refers to the way that team members interact with each other [17]. It has been referred to as group morale [67], interpersonal attraction [55] and team compatibility [56]. It is closely related to *Team Coordination*, as teams that are less cohesive may not coordinate as efficiently as other teams. Members of cohesive teams are able to work together within their roles to complete tasks effectively. *Team Cohesion* includes group morale and group attitude toward the task. Mullen and Copper [16] distinguish three facets of team cohesiveness: interpersonal attraction of team members, commitment to the team task, and group pride and team spirit.

One such interaction where a team was not cohesive can be seen in HERA event [57], XHE3:

> Management did not defer to the expertise of the system engineer. This is characteristic of teams with an inappropriate balance of power.

4.2.5 Role Awareness

Role Awareness is related to how each team member perceives his/her duties, responsibilities, and role as a team member. It is related to how the team divides tasks and how team members interact [55, 68]. Workers in NPPs have defined roles and it is necessary for every team member to comply with expectations of his/her role. *Role Awareness* has two main functions: to ensure that tasks are completed and to enhance team coordination.

Role Awareness requires workers to be aware of their place in the team and to act according to the expectations of the role. Shift Supervisors have different duties than Reactor Operators during an unplanned situation – if one member of the team deviates from the expected role it can have a negative impact on teamwork and on the evolution of the situation. Proper role awareness ensures that all necessary tasks are completed and reduces conflict among team members. A team cannot properly function without a leader, but a team also cannot function with too many leaders. One example is:

> The onsite and operations managers were above the shift managers, and it seems that they were too involved in what was going on, assuming responsibility that

they should not have. It is inferred that the roles and responsibilities of each person were poorly understood by those involved ([62], XHE0.6).

4.3 Person-based Factors

Person-based PSFs are internal factors that affect each individual. The person-based factors encompass the worker's state of mind, temperament, and various intrinsic characteristics. People may act as a member of a team and an organization, but every individual has a unique working style and unique perception of a situation. Organizational culture cannot fully account for the behavior of every member of the organization because each person has unique internal factors.

The person-based PSFs include the person's physical and mental fitness and suitability for the task. Physical and psychological fitness have been treated as a single PSF because it is very difficult to separate one's physical abilities from one's psychological state, both in practice and by definition.

Psychological and physical abilities should not be confused with knowledge and experience. Experience relates to the knowledge possessed by the worker, whereas the PPA refer to the readiness of the worker to *use* that knowledge. Cognitive biases and abilities, including knowledge, are also unique personal factors. Unlike the organization-based training PSF, which is generally uniform for personnel throughout a department, knowledge and experience are unique to every person and are therefore a person-based factor. Information from training is converted into knowledge, but different people will always retain different information from training. The retention of knowledge could also be related to other person-based factors including attitude and morale.

In the span of an event, most of the person-based factors are static, especially when compared with the stressor-based factors. Intrinsic characteristics, work style, knowledge, and abilities are unlikely to change in the short-term of an event. The person's perception of the situation will change over the course of an event, but the person's intrinsic characteristics that affect how they form perceptions will not change.

Many of the person-based PSFs are unobservable because they cover internal states. Because of the difficulty of observing a person's internal characteristics, it is necessary to include behavioral indicators in lieu of actual PSFs. The way the person prioritizes information may affect the state of the situation, but it is not an influencing factor on that person's current performance. However, the way the person prioritizes information is an indicator of aspects of the personal work conduct. In the current model, work conduct is the only PSF with explicitly associated behaviors, but future versions of the model may include behaviors for other unobservable PSFs.

4.3.1 Attention

Attention refers to how the worker distributes the available cognitive resources. It is comprised of attention to the current task and attention to the surroundings.

4.3.1.1 Attention to Task

Attention to Task is the ability of the worker to focus on a task. Attention can be affected by many external distractions and it can also be affected by internal thoughts and distractions such as emotional state. Attention is influenced by the number and complexity of tasks, communication with others, and background noise and activity. Workers must properly balance attention to task and attention to surroundings to ensure that they are focusing on the task at hand but not becoming so involved in the task that they do not notice critical changes in the background. An example of LTA *Attention to Task* is:

> The Unit 2 supervisor was with the RO, focused on addressing the malfunction of the channel N-31 Source Range indicator malfunction. His attention was not on the BOP operator's actions (inferred). ([58], XHE4)

4.3.1.2 Attention to Surroundings

Attention to Surroundings is involves being aware of the state of the environment, the actions of other workers, and other surroundings. This includes much of the information that is registered passively while completing tasks. One such example is noticing alarms – if an operator is completing a routine task, the operator passively registers that there are no alarms ringing. However, once an alarm starts sounding the operator will notice the change in background noise.

4.3.2 Physical and Psychological Abilities

Physical and Psychological Abilities (PPA) refer to the mental and physical resources available to the individual while in the workplace. This includes alertness, sensory limits, and fitness for duty [12] and also to situations where the workers physical ability falls outside of the normal range anticipated in the HSI design [69]. In the HERA database it is represented as "Fitness for Duty non-compliance," "Circadian factors / individual differences," or "Impairment". PPA can be altered by the use of alcohol and illegal or legal drugs, or the absence of necessary prescription drugs. PPA an also be affected by the emotional state of the worker. A worker can also be temporarily affected by physical things outside of work, such as fatigued muscles from exercise or low blood sugar levels. PPA also includes the natural abilities of the worker as influenced by circadian rhythms.

Psychological and Physical Abilities should not be confused with *Knowledge & Experience* or *Training*. Training, knowledge, and experience relate to the knowledge possessed by the worker, whereas the PPA refer to the readiness of the worker to *use* the knowledge possessed.

Both physical abilities and psychological abilities have been included in this PSF because it is difficult to separate entirely physical versus entirely psychological responses. Psychological states can affect one's physical performance and physical condition can affect one's psychological state. The constant interplay between physical and psychological states allows for the argument that they cannot be differentiated and at the core they have the same effect.

4.3.2.1 Fatigue

Fatigue relates to the physical and mental weariness resulting from too little sleep or too much work. It's the basic state of feeling "worn out." Fatigue relates directly to the Physical and Psychological Abilities PSF, because fatigued workers may have reduced physical capability and slower or less effective cognitive responses [70]. Fatigue can be affected by work hours, work breaks, shift rotation, and night work [15, 22]. One example is:

> Worker had just switched to working the night shift and complained of sleepiness toward the end of the shift. (Hypothetical Example)

4.3.2.2 Alertness

Alertness is related to the "awakeness" of the worker as it relates to responding to planned or unplanned demands. It refers to the amount of attention available to be distributed among the tasks. Reduced alertness can affect the cognitive abilities of the worker. An example of decreased *Alertness* is:

> Persons working the night shift experience decreases in cognitive abilities and alertness, even if they are accustomed to the shift. It is inferred that the time of day contributed to the error. ([64], XHE9)

4.3.3 Morale/Motivation/Attitude

Morale, Motivation, and Attitude (MMA) together refer to style [68], temperament [71], personality [11, 56], and intrinsic human variability [72]; in the remainder of the dissertation this PSF is referred to as *MMA* or *Attitude.* These characteristics manifest as willingness to complete tasks, the amount of effort a person is willing to put into tasks, and the state of mind of the worker [73, 13]. Just like each organization has a different values and motivators, people also have unique underlying influences. *Morale, Motivation, and Attitude* can be affected by external factors such as *Organizational Culture, Teamwork*, and *Resources*, but each person will internalize these factors differently leading to varying MMA even among team members.

"Personal Work Practices" are included in many HRA methods as a PSF, but they are not actual PSFs, rather they are behaviors that indicate morale, attitude or intrinsic characteristics of the person that prescribe the way they behave. Since it is extremely difficult to measure attitude, especially in retrospective analysis, it is necessary to include specific work practice behaviors as metrics of attitude. The behaviors identified during review of the HERA data are problem solving style, information use, prioritization, and compliance.

4.3.3.1 Problem Solving Style

Problem Solving Style refers to the way which people and teams approach a problem. It includes the way that people communicate with each other as well as the non-vocalized thought processes. It is related to hastiness behavior ("quick way of working" [68]). People may adapt different problem solving styles based on the composition of the group. Examples of different problem-solving strategies can be found in [41].

Woods et al. identify five different problem solving styles in [74]. They include the vagabond, hamlet, fixation prone (garden path), inspector plodder, and expert focuser. The vagabond jumps from issue to issue without satisfactory resolution of any issue. The hamlet looks at each situation from multiple viewpoints and considers many possible explanations of observed findings. The fixation prone person persists on a certain issue or activity. The inspector plodder exhibits very thorough consideration of evidence and possible explanations via explicit chains of reasoning and then narrows in on possibilities). The expert focuser is adept at seeing and focusing in on the critical data from the current context so that he/she is always working on the most relevant part of the situation.

An example of LTA *Problem Solving Style* is:

> This decision reflected the operating crew's lack of the 'big picture.' They were focused on RCS temperature and pressurizer level to the exclusion of other important issues, such as pressurizer pressure and bulk temperature. ([75], XHE7)

4.3.3.2 Information Use

Information Use does not necessarily shape performance, but it is an indicator of a factor that does shape performance. The *Work Practices* PSF in many HRA methods is largely unobservable and subjective. For retrospective analysis it is nearly impossible to assess the "work practices" of a worker without citing the behaviors that indicate the person's work style.

The *Information Use* behavior relates to how well people use the information presented to them. Information use can relate to both written information and information from the HSI. It is important to recognize how the human uses information, because if the HSI is providing the correct output in a visible place, but the human does not look at it, it is not a system failure, it is a failure of personal work practices. Inadequate *Information Use* may entail information that is present but not properly used or failure to access any/all available sources of information. *Information Use* is linked to *Bias* because people may exhibit bias toward or against certain information sources. Examples include:

- Indications of RCS temperature and pressure were available in the control room to identify the cause of the pressurizer level drop, but the crew did not adequately use this information.([59], XHE13)
- Operators did not refer to any procedure during their investigation of the depressurization, but instead relied on their recall of procedures and plant behavior. ([76], XHE1)
- Personnel had access to vendor manual specifying set point volt per cell requirements but did not reference it.([51], XHE2)

4.3.3.3 Prioritization

Prioritization is how an individual chooses to order tasks, including situations where conflicting goals must be prioritized. Like *Information Use*, it is a behavior and not a PSF, but it is another observable aspect of personal work practices. Workers are typically assigned a number of tasks at the same time and often the worker must decide how to prioritize the tasks. In NPPs tasks should be prioritized by safety significance, but this does not always happen. Some tasks may be deprioritized due to time concerns, difficulty of the task, or other internal motivations.

Naturally, *Prioritization* is subjective and it may be related to *Knowledge and Experience*, as experienced personnel may be more familiar with the plant and may be able to prioritize tasks more accurately. One case of LTA *Prioritization*is:

> Crew attention was inappropriately diverted from the primary systems to the balance of the plant. They were more concerned with restoring CW pumps and avoiding a turbine trip than properly controlling the reactor during the rapid downpower transient. ([66] XHE12)

4.3.3.4 Compliance

Like the other aspects of personal work processes, *Compliance* is an observable indicator of the PSF. *Compliance* refers to how well people follow directions or adhere to policies established by the organization or the industry.

Compliance provides insight into the employee's work practices. It demonstrates how seriously the person takes the rules. Worker compliance can be influenced by the *Organizational Culture*; a lax organization will engender lax compliance among its workers. One example is:

> Operators did not follow the steps listed in the procedure and failed to shut

> down the Control Rod Drive (CRD) system. Operators executed some steps in section 1 of the procedure, but not all required steps. Step 1.7 stated, If RWCU is NOT running and Control Rod Drive (CRD) System is NOT required for vessel inventory, SHUTDOWN CRD system. The RPV water level was being adequately maintained by a combination of HPCS, RCIC and feedwater, so the CRD system should have been shut down in accordance with the procedure. In contrast to the procedure requirement, the Operators failed to execute Step 1.7 and shut down the CRD system. ([77], XHE4)

4.3.4 Knowledge and Experience

Knowledge is the worker's understanding of the system design, purposes, elements, functions, and operations, in relation to the workers responsibilities, position, and the specific activities or tasks being undertaken [11, 14, 25, 78]. *Experience* is the accumulation of information and knowledge gained through training and interactions with the system [68, 79, 80]. It is difficult to separate knowledge from experience because knowledge is often acquired through experience, but less experienced personnel are not necessarily less knowledgeable than their experienced counterparts.

The *Knowledge and Experience* PSF is related to training, as knowledge is gained through training, but the training is not fully responsible for knowledge. One major difference between *Knowledge and Experience* and *Training* is that *Knowledge and Experience* differs for every member of a crew, but all members undergo the same *Training*. Information from training is converted into knowledge, but different people may retain different information from identical training courses. *Knowledge and Experience* also relates to *Staffing*, because proper staffing will ensure a proper knowledge and experience before training and a proper balance of expertise on work teams. Examples of *Knowledge and Experience* include:

- Operators did not understand the cause of the ADVs and TBVs staying open.([75], XHE6)
- Licensee failed to recognize that the SIAS reset function was safety related and seismic category-1, and incorrectly concluded that logic system functional testing was not required. ([75], XHE3)

4.3.5 Skills

The *Skills* PSF is closely related to job-related knowledge and experience. *Skills* refer to the abilities of the worker to do 'work of the craft,' necessary task-related abilities that require little cognitive effort. LTA skills can result in time delay for necessary actions or reduced work quality [15, 12, 60]. One example of LTA *Skills* is:

> Worker did not have the technical prowess to align indicators to the necessary level of precision. (Hypothetical example)

4.3.6 Familiarity with Situation

Familiarity with Situation refers to the similarities the worker perceives between the situation and the worker's general industry knowledge and previous experiences [80]. *Familiarity with Situation* includes the IDAC PSF "Memory of Recent Diagnoses, Actions, and Results," which refers specifically to familiarity with the system at hand [67]. The familiarity PSF overlaps with *Knowledge and Experience* and *Bias*. Workers with more experience likely exhibit familiarity with more situations and remember more past diagnoses than inexperienced operators. However, workers with familiarity with many situations may also exhibit bias toward certain conclusions based on previous experience despite indicators to the contrary.

Lack of familiarity can occur when unanticipated situations arise, including situations that were not covered in training or situations that were dismissed as impossible. Familiarity with a situation is more complicated, because people with more familiarity with a system may diagnose and solve system problems faster. However, people very familiar with a situation may not consider indicators that make the situation unique. It may also impact teamwork because familiar personnel may discount the concerns of less experience team members. One example is:

> Operators were unfamiliar with the icing phenomenon and did not know how to deal with it properly, repeated problems with icing on the ESW system; inferred high stress. ([64], XHE16)

4.3.7 Bias

Bias is the tendency of humans to make conclusions based on selected pieces of information and the exclusion of information that does not agree with the conclusion. *Bias* may appear as confirmation bias, i.e., looking only for information that supports one's hypothesis, belief bias, i.e., selecting information to to reinforce one's own personal beliefs, and averaging bias, i.e., regression toward the mean [81, 82]. Bias may be demonstrated by operators attempting to reinforce their own suspicions while ignoring information to the contrary. Bias may result from previous experiences, specific training, etc. *Bias* refers specifically to situations where the worker disregards some available information in an attempt to seek out information to confirm his/her theory. One such example is:

> The relief-crew supervising operator had interpreted that the Train 'B' ESWS operability was not challenged because he believed that the ESWS discharge pressures had not changed. Based on this mindset, he discounted the significance of the operator's report of decreased Train B ESWS intake bay level. ([64], XHE14).

4.4 Machine (design)-based factors

Machine-based PSFs refer to the system as designed by the manufacturer. All of the mechanical and electrical components of the system are part of the machine system, but the building is also included in the "machine" because it is designed along with the components of the mechanical system. The machine-based PSFs consider the entire system as purchased, which for the most part cannot be modified without significant cost and effort.

Machine-based PSFs can be distinguished from situation-based PSFs because machine-based PSFs are the static physical (and software) parts of the system that are generally unchanging over the course of an event. This also differentiates machine-based PSFs from organizational PSFs by defining who has control over the part; the design of the containment building is something that the organizational cannot influence because it has been previously designed. However, the lighting in the containment building can be controlled by the organization because the organization, not the designer, has responsibility for changing light bulbs. However, if the containment building does not have enough lights by design, it is a machine-based problem.

4.4.1 Human-System Interface

The *Human-System Interface* PSF covers how information is communicated between humans and the machines. The *HSI* PSF is not limited to the operator interaction with the control panel. It refers to the way that any worker interacts with the system, including maintenance workers. It includes ergonomics, usability, and physical access.

There are two ways that humans interact with machines: providing input and receiving output. Humans interact by giving input to the machine in ways such as turning a dial or entering a command on a keyboard. The HSI should be designed to maximize the ability of the human to provide input to the machine. The *HSI* PSF considers arrangement of equipment / layout of the system [61, 60]. Poorly designed HSI could include inaccessible displays, difficult-to-turn dials, or tasks that require contorting the body to be completed.

Humans also interact with machines to get information (machine output). This includes reading analog and digital output. Humans must be able to get to the physical location of the output device, and they must also be able to clearly read the output. Inaccurate labels, display range, or markings could prevent the human from getting the correct output [11, 61, 60]. If the human is able to access the device and chooses not to, it is a personal work practices issue, not an HSI problem. Examples of LTA *HSI* are:

- No fire alarm lights were readily visible to the plant operators. The fire alarm panel was not located so as to be easily seen and noticed by the plant operators. ([83], XHE4)
- The maintenance activity was being performed in tight quarters.

4.4.2 System Responses

The *System Responses* PSF refers to the system feedback, or specifically the the difference between the responses given by the system and the responses expected by the worker. The *System Responses* PSF is related to the *Complexity* PSF because inadequate or unexpected system responses can create ambiguous situations which are then more difficult to interpret than situations with straightforward system responses. Examples of the Perceived System Response PSF in literature include feedback [22] and expectancy set [60]. An example from data is:

> Operators were confused by the contradictory indications of the 241Y bus status. It was not immediately clear that the bus undervoltage protection circuitry had suffered a fuse failure. Operators also had to deal with the reactor trip, the fluctuating RPV water level, entering abnormal procedures, and equipment that would not perform as expected (RHR). ([77], XHE3)

4.5 Situation-based Factors

Situation-based PSFs are characteristics of the scenario that are likely to affect human performance. These characteristics are external to the human and the system, and they tend to be dynamic. Situation-based factors differ from machine-based components because the system factors can change during the scenario. These changes can be due to natural causes, e.g., weather, or can be due to actions executed earlier in the scenario. A non-working piece of hardware is not a situation-based factor unless it is a failure that occurred during and is repaired by the end of the scenario. Situational factors include the way the scenario is evolving due situational complexity, the number of simultaneous tasks, the status of the machine and the work environment.

Many of the situation-based PSFs are closely related to the stressor PSFs. Human perception is the dividing line between situational and stressor PSFs. While task complexity is subjective depending on the worker, it is still possible to estimate the relative complexity of a situation from the perspective of the “average” worker; there are scenarios which can be clearly labeled more complex. An SGTR event may seem simple to very experienced personnel and complex to less experienced workers, but an SGTR event coupled with broken SG level indicators will always be more complex than an SGTR event with properly functioning indicators. It is this objective complexity that is captured by situation-based PSFs.

4.5.1 External Environment

External environment is the characteristics of the scenario external to the person that cannot be controlled or modified by any person/group. Environmental factors can include excessive high or low temperature or humidity, noise, poor lighting or other external weather factors [84]. Work environment refers not only to the external conditions as they affect the human's performance, but also to the ways in which environment may affect the accessibility of certain parts of the system. In control room activities the environment is usually controlled, but during severe situations they can be affected by fire or radiation [22]. In maintenance scenarios the environment typically has more impact because maintenance can be subjected to different weather conditions outside or in sections of the plant. An example is:

> Work took place in containment, a radiation environment. Concerns for dose likely contributed to the decision to take no action for the leaking flange. ([52], XHE20)

4.5.2 Hardware & Software Conditions

Hardware & Software Conditions (Conditioning Events) are the external events or latent machine failures that contribute to scenario evolution [15, 61]. These conditions may result in abnormal, ambiguous or conflicting system output [25]. Conditioning Events increase cognitive effort due to conflicts between the observed system or conflicting system output [85].

Less-than-adequate hardware or software conditions may be the result of machine aging, inadequate maintenance etc. [14]. The HERA database captures conditioning events *Complexity* section in several PSF details, including "loss of functionality of multiple systems," "presence of multiple faults" or "unavailability of multiple systems due to maintenance." Conditioning events differ from the expected system responses PSF because conditioning events refer to the mismatch between system output and "normal" system operation, whereas *expected system responses* refer to an inaccurate mental model developed by the worker. One example is:

> 22 steam generator feedwater pump (SGFP) tripped unexpectedly; ADVs and TBVs malfunctioned and did not respond as designed, remaining full open, causing an uncontrolled RCS cooldown. ([75], XHE6)

4.5.3 Task Load

Task Load refers to the actual task demand assigned to a person in terms of the number and type of tasks (varying complexity, importance, fault tolerance, etc). These tasks can be simultaneous or in sequence. The duration of tasks must also be considered, because having many long tasks may result in even greater stress than having many short tasks. Task load is a component of the perceived workload [15]. It typically applies in cases where there are too many tasks assigned to one person, but there may be cases where having too few tasks can lead to errors due to worker complacency. *Task Load* is related to the *Task Scheduling* PSF because effective task scheduling will ensure that workers are not overloaded with scheduled tasks. *Task Load* can also be impacted by unplanned or emergency events. The number of tasks is relevant to errors because high task load could result in workers rushing to complete tasks without quality checks. It can also influence the stress level of the worker. For example:

> Between the time that the reactor operator announced that the ESW system alignment needed to be reviewed and shift turnover, operators had to deal with multiple equipment problems: the auxiliary boiler tripped, five control rods failed to fully insert, requiring emergency boration, and the turbine driven auxiliary feedwater pump was declared inoperable due to failed packing in the inboard shaft packing gland. It is inferred that the state of the ESWS alignment had slipped from the crews' minds. ([64], XHE12)

4.5.4 Time Load

Time Load is similar to *Task Load*, but it adds the element of perception of time to the number of tasks; this time perception can affect worker stress beyond the stress of having too many tasks [86]. In *Time Load* situations, the worker is expected to complete a specific task or a number of tasks in a certain time. If time load is LTA, the worker perceives the time limit to be too short and this perception can affect the stress level of the worker. Like *Task Load, Time Load* may also have infrequent cases where too much time could contribute to error. Errors can occur during LTA *Time Load* situations because workers may rush through tasks, skip quality checks, limit communication and teamwork, or fail to complete tasks. *Time Load* is difficult to assess in retrospective analyses. Time load should be interpreted from the perspective of the "average" worker or a worker at least one professional level above an entry-level position. Some examples are:

- The RO was projecting a sense of urgency regarding the RCS cooldown, and the BOP operator felt pressured by this. ([58], XHE5)
- The SS instructed the operator to perform the alignment without procedural guidance for expediency; there was pressure to perform the alignment quickly. ([64], XHE7)

4.5.5 Other Loads

Other Loads refers to the tasks beyond those necessary for the work at hand. Tasks directly relevant to the work are *Task Load* factors, but other tasks, including things like communication are considered other loads. *Other Loads* can be considered any routine tasks that are not necessarily covered in training. For retrospective analyses it is difficult to differentiate between *Task Loads* and Other Loads, so these are likely to be merged into a single PSF for many analyses. For some simulator applications or in depth qualitative analyses the other loads can be addressed as either *Non-task Load* or *Passive Information Load*.

4.5.5.1 Non-task Load

These *Non-tasks Loads* can be differentiated from *Task Loads* by treating tasks as things that are designed and trained for, and non-tasks are things that are necessary to complete one's work but are generally outside the scope of training. While communication may be a work-relevant task, it may be non-essential in the maintenance of simple parts. These work-relevant non-task loads include interfering activities [60].

4.5.5.2 Passive Information Load

The *Passive Information Load* includes the information and cues presented by the external world [22]. A high passive-information load can lead to stimulus overload [87]. These stimuli including indicators, alarms, environment and other parts of the background.

4.5.6 Task Complexity

Task Complexity refers to the cognitive and physical demands of the task at hand. *Task Complexity* considers the difficulty of diagnosing and executing work, the amount of knowledge required to complete the task, the number of steps required to complete the task, the precision required, and the ambiguity of the situation.

Complexity also includes the mental and physical effort required to execute the selected problem solving strategy for the task (see [41] for nine general problem solving strategies).

Complexity from the perspective of the actor is difficult to judge during a post-event analysis. While actor experience will impact the perception of complexity, the analysis in HERA are based on expert judgment. Without dependence on experts complexity can be judged from the perspective of an actor with a minimum number of years post-training experience in the job role, or based on the qualifications necessary to advance past an entry-level position. The *step complexity measure* [88] can also be used to calculate the complexity of performing a procedure step. An example of complexity captured in HERA is:

> Operators received ambiguous feedback due to rapid changes in availability of offsite power. ([89], HS2)

4.6 Stressor-based Factors

Stressor PSFs are the demands of the situation as perceived by the person. The external loads manifest in the person as tension or arousal [22] that may disrupt or facilitate performance. The IDAC model [67] includes four types of stress: pressure, conflict, frustration, and uncertainty. Urgent matters that require immediate attention result in a feeling or pressure. Multiple incompatible goals result in conflict stress, while the perception of a blocked goal leads to frustration. Inability to fully understand and plan an appropriate response to situation results in uncertainty.

The different types of stress differently influence worker performance. Large demands could result in a worker feeling pressure and increasing the internal resources (e.g., attention) used to meet the demand. Individuals may respond to conflict stress by changing certain goals or obtaining additional external resources. They may respond to frustration caused by blocked goals by altering the goals or the methods used to achieve the goals. They may respond to uncertainty by attention to gather additional information or other resources to better understand and respond to the situation.

It is important to emphasize the role of perception in this category the loads are objective characteristics of the situation, but the perception of the loads is what makes them a stressor. Individual perception serves as the filter that turns situational characteristics into an internalized load. The subjective loads can increase based on the perception of the objective difficulty of diagnosing and executing work, the amount of knowledge required, the number of steps required, and the ambiguity of the situation. The number of alarms flashing is objective, but the perception of the alarms is what creates stress. The perception of the alarms can vary between personnel and can also vary within the same person depending on the state of other PSFs. Each person performs an individual situational assessment and forms individual perceptions of situational severity and urgency. The inclusion of perception as a major aspect of the stressor PSFs limits the definitional orthogonality of the this PSF group. Personal characteristics covered in the person-based PSFs will always have some amount of influence over how a person perceived situational demands. Likewise, the perception of the situation cannot be completely independent of objective situation-based factors.

4.6.1 Perceived Situation Severity

The *Perceived Severity of the Situation* is a personal assessment of the magnitude of the impact of the situation and its potential consequences. Possible outcomes could adversely affect the worker(s), the plant, or the general public. Perception of severity could be influenced by attitude, but attitude may also be affected by the personal assessment of severity.

In NPPs, scenarios are generally interpreted to have a potential negative impact. This means that severity can only be assessed in relation to increasing or decreasing the potential for negative impact. Severity is measured on a spectrum from marginal to extremely severe cases. The *Perceived Severity* PSF does not necessarily have a positive aspect where there are potential extremely desirable outcomes. The most desirable outcome is that there is no negative impact. There are very few ways to have a significant positive impact the personnel, public, or the plant; there are really only non-negative outcomes. A “positive” impact on the general public would be to have no impact at all, i.e., to avoid any negative impact. A worker is not going to take an action that dramatically improves the plant or helps the public – a worker is going to prevent negative impact; positive outcomes in NPPs are the absence of any negative outcome. One example of a severe situation is:

> Plant trip recovery and dealing with heavy smoke and possible fire. ([83],

> XHE6)

4.6.2 Perceived Situation Urgency

Much like the severity of the situation, the *Perceived Situation Urgency* is a personal assessment of the situation. It is an assessment of how quickly an undesired outcome is approaching and affects the perceived Time Load. Perceived urgency indicates how close the worker believes the system is to the state of failure. A similar concept in literature is the rate at which the situation moves towards the moment at which negative consequences materialize [69]. One example of *Perceived Situation Urgency* is:

> The RO was projecting a feeling of urgency, which put pressure on the other crew members.([58], XHE4)

4.6.3 Perceived Decision Responsibility

Perceived Decision Responsibility is the perceived responsibility and accountability that a worker has to make decisions or actions. Individuals must consider the impact that the decision will have on the plant, the public, and also themselves when implementing a decision. Individuals may have to weigh several impacts and make the optimal decision, including where the blame will be placed if failure occurs. An individual may take a different course of act depending on his or her sense of responsibility. Individuals may exhibit more or less risky behaviors if they have to account for the actions later [69]. A decision that is made based on a procedure would have a different perceived decision responsibility than a decision based on the operators own knowledge.

One example of this can be seen in the IDAC analysis of a HI-HI Intermediate Range Monitor Scram at Monticello [42]. The Shift Manager had to make the decision between shutting down by switch mode or inserting control rods notch by notch. Shutting the plant down notch by notch is the plant policy (to reduce wear and tear on the Control Rod Drive Mechanisms). The Shift Manager had an informal conference with the Plant Manager and the Site Superintendent before making the decision.

Shift Manager responsibility load was high:

1. He wanted the decision of shutting down the reactor to be taken collectively.
2. Selection between available shut down options was based on plant policy, not plant needs. ([42], Monticello 2-5)

Chapter 5

Methodology for Development of a Causal Model of Performance Shaping Factors

Causal models are present in many aspects of Probabilistic Risk Analysis (PRA), but models play an especially important role in Human Reliability Analysis because of the invisible nature of human cognition. This chapter introduces a methodology to develop a data-informed causal model of the relationships among Performance Shaping Factors (PSFs). The final product of this methodology will be a Bayesian Belief Network (BBN) which visibly displays the relationships among the PSFs and which links these PSFs to error.

A causal model is a diagram consisting of nodes (i.e., the variables or PSFs) and directed arcs (i.e., causal influence between nodes); a BBN is a specific type of causal model. Bayesian analysis offers a framework to analyze and combine multiple types of data and has previously been used in PRA applications with limited data [90]. The BBN offers the flexibility to update the analysis by adding different pieces of information to the model as they become available. This is especially beneficial for HRA, since HRA data comes from many different sources. Bayesian analysis has a long history of use in various industries; these industries fall across the risk spectrum, including ecology [91, 92], food safety [93], national security [94], criminology [95], etc.

The methodology proposed in this chapter can be used to develop a data-informed causal model. Due to the subjective nature of HRA, there are no benchmarks that can be used to validate a model. HRA analysts generally rely on expert opinion to develop models. The data-informed approach to modeling uses expert opinion, and it uses data to add another level of validity beyond expert models. The methodology presented is not limited to use with the HERA database. It can be applied to any data set that contains assessments of the state of PSFs.

5.1 Bayesian Belief Network Overview

5.1.1 BBN Structure

In a BBN, each variable is represented as a single node. Relationships are indicated with directed arcs. The nodes must be defined in such a way that each node is a distinctly defined entity, even if it is causally influenced by other elements. For example, *Procedure Adequacy* can be broken down into *Procedure Availability* and *Procedure Quality*. In a BBN we can define three separate nodes and we can logically connect them to indicate that *Procedure Adequacy* is influenced by both availability and quality of procedures.

The first step in development of the causal model is to identify the variables to be included as nodes in the model. This is not a trivial task since the variables in the model must be distinctly defined. The second step is to identify the relationships (arcs) between the variables. The arcs are used to represent a causal relationship between two variables, with the arrowhead indicating the direction of the influence.

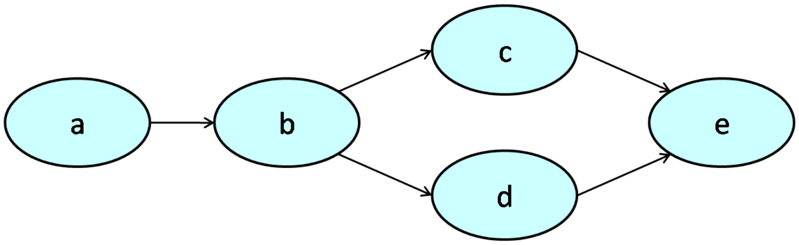

Figure 5.1: Sample BBN diagram for five nodes

In Figure 5.1 there are five nodes. Node a is a root node; it has no arcs pointing into it. Node e is an end node; it has no arcs pointing out of it. Nodes b, c, d each have one parent node and node e has two parent nodes. Nodes a, c, d each have one child node and node b has two children.

5.1.2 BBN Quantification

Once all relationships among BBN nodes are indicated by arcs, each node is assigned a marginal or conditional probability table. These probability tables contain all known information concerning the state of the system based on both expert opinion and available data. In a BBN each node is assigned a probability distribution based on the possible states of its parent nodes. Once each probability distribution is set, the initial model is complete. As new information becomes available (e.g., evidence about the state of one node), the probabilities of all nodes in the model can be automatically updated based on the evidence.

Each node in a discrete BBN has a finite number of possible states. Many BBNs use binary nodes, where 0 and 1 represent the positive and negative states of the node. The sum of the marginal probabilities of all states within the same node must equal 1.0. Each possible state of a root node is quantified with the marginal probabilities of the states. In Figure 5.1, node a would be the only node quantified with marginal probabilities. Assuming that a has two possible states, the probabilities would be $Pr(a) = p$ and $Pr(\overline{a}) = 1 - p$.

Nodes with one or more parents are quantified with conditional probability tables. The size of the conditional probability table depends on the number of parents. The conditional probability table will contain values for every possible combination of states of the node and its parents. For a binary node with n parents, the conditional probability table will contain $(2^{(n+1)}/2)$ columns. Each column in the conditional probability table must sum to 1.0.

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

Table 5.1: Conditional probability table for node b with single parent a

The conditional probability table for node b is displayed in Table 5.1. The conditional probability tables for c, d will be the same size as Table 5.1. The table for node e will have 8 columns. The reader is referred to the references for additional information about conditional probability in Bayesian networks [96, 97, 98].

Conditional probabilities can be populated by using expert opinion, data, or a combination of both. The method used to develop our model is presented in section 5.4. Additional methods can be found in a special issue of Reliability Engineering and System Safety dedicated to quantifying BBNs [99].

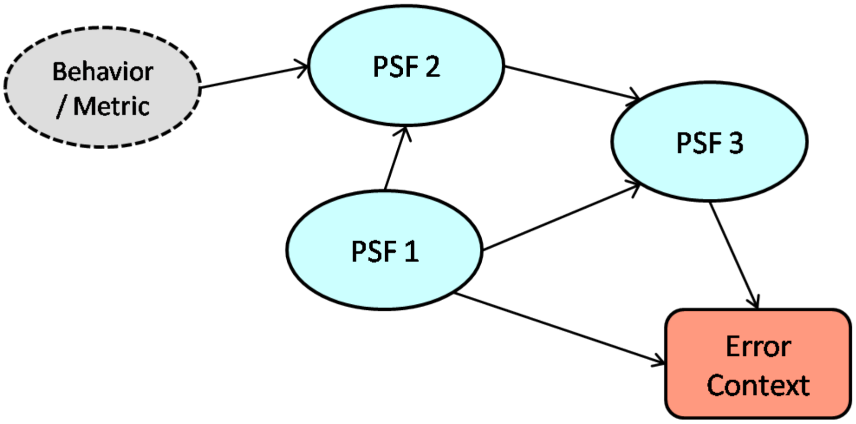

Figure 5.2: The basic elements of a causal model including directed arcs between PSF, metric, and error context nodes.

5.1.3 Analyst Use

The fully quantified BBN represents the prior knowledge for an analyst. To use the model, the analyst will make observations (set evidence) about certain nodes and examine the impact on specific nodes of interest. By setting evidence, an analyst is proving new information to inform the model. This produces updated probabilities for all nodes in the model.

Analyst evidence is often the observation of a particular state of a node. The analyst sets the evidence in the BBN and the network updates probability of each node based on both prior observations and new evidence. For nodes where there is no evidence, the network relies on the prior probability. Once the BBN is complete, it can be incorporated into a PRA by linking BBN nodes to other risk models.

5.2 Model Development Procedure

Development of the causal model of PSF interactions is a multi-step process. This section presents the procedure for creating a PSF model with limited discussion of the quantitative techniques used in the procedure. Additional details about the quantitative techniques are presented in Section 5.3. The procedure presented in this section can be applied to create different causal models with varying degrees of specificity depending on the PSFs selected. Applying the entire methodology will result in a causal model like the one displayed in Figure 5.2.

5.2.1 PSF Set

The PSFs that can be included in the model depend on the quality and quantity of available data and expert information. The PSF hierarchy presented in Chapter 3 is designed to accommodate various amounts of information. The hierarchy can be collapsed to create base models and then expanded as additional information becomes available. Early PSF models will use a smaller set of PSFs, while models created with more information can include a greater number of PSFs.

Selecting the PSF set is the most resource intensive step in the methodology, but it is also the most important. Careful selection of the PSF set is necessary to produce a valid model. The PSF set must meet the fundamental criteria presented in Chapter 3. The analyst should screen the initial PSF set to verify that these criteria are met.

The choice of which PSFs to include in the model can be done based on expert judgment or it can be done through a systematic, iterative process wherein quantitative analysis is performed and the PSF set is refined, based on the quantitative results, until a suitable set is selected.

PSF selection begins with correlation analysis on the full PSF set [1]. Ways to refine the PSF set include merging similar PSFs (e.g., *Procedures* and *Tools* become *Resources*, dividing a PSF into more categories (e.g., *Procedures* becomes *Procedure Availability* and *Procedure Quality*) or eliminating the PSF entirely. With the PSF set presented in Chapter 3, it is suggested to start the analysis at the bottom level of the hierarchy and then to collapse the hierarchy one PSF at a time.

The analyst should examine the correlation results to identify correlations that are erroneous (e.g., correlations exceeding $|0.95|$ tend to be erroneous in the HERA data)[2]. Depending on the correlation technique used, the correlation set can be further refined based on significance values or sensitivity analysis. See Section 5.3 for discussion of correlation techniques that can be applied to data from the HERA database.

Once outliers are identified and removed, factor analysis (FA) is used to further refine the PSF set. It is left to the analysts to determine which FA model and

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[1] PSFs that are present in fewer than 10% of the sub-events are likely to produce erroneous factor analysis results [100] and could require expert judgment to be placed in the model. Similarly, PSFs that are present in more than 90% of the sub-events may require expert judgment or additional parsing before they can be placed in the model. It may be beneficial to eliminate these PSFs before running the quantitative analysis to reduce the computational burden.

[2] What is seen as erroneous will vary based on the data set and the analyst. The intention of this step is to allow analysts to remove known outliers without devoting computational resources.

technique is most suitable for their data. Choice of software package is also left to the analyst. However, software must be able to allow analysis to continue even if Heywood cases occur, i.e., correlations exceed |1.0| [101]. While Heywood cases are undesirable, they are useful for our analysis because they point to specific limitations in a data set or model. Heywood cases can be eliminated by adding data, by trying a different factor model, or by eliminating outliers.

The analyst should examine the FA results and identify the PSFs producing Heywood cases. The PSF with the largest spurious correlation should be revised by merging it with another PSF, dividing it into more PSFs, or eliminating it from the quantitative part of the analysis. After removing the largest Heywood case, the factor analysis is repeated. This process is repeated, removing one Heywood case at a time and then running a new FA, until factor results are free of Heywood cases. Once all Heywood cases are removed, the analyst may wish to perform significance tests to determine if the factor model is suitable for the final PSF set. If the most significant factor model differs from the factor model used to refine the data set (i.e., if there is a different numbers of factors), it is advisable to repeat the entire process with the new factor model; this ensures that the final PSF set is based on the most significant factor model.

5.2.2 Directed Arcs

Once the set of PSFs has been finalized, the initial structure of the model is developed by using correlation analysis. Each PSF becomes a node in the model and arcs are drawn between variables with correlations $> |m|$. For analysis of the current data, $m = 0.3$; this correlation cut-off value may be adjusted for different data sets.

The direction of the arc is based on expert information. This information may come from literature, current models, or direct expert elicitation. For models that contain both data-driven and expert informed nodes, it is advisable to differentiate between the arcs rooted in the data and the arcs rooted in expert judgment. Solid arcs should be drawn between nodes with correlations exceed $|m|$ or where direct logical relationships exist. Dotted arcs should be drawn where expert opinion is used to identify relationships. If no clear logical relationship between two PSFs exists, but the correlation exceeds $|m|$, the nodes may have a common parent node, or they may be part of the same Error Context.

5.2.3 Error Contexts

One difficulty associated with the use of correlation results is that without further analysis, we cannot differentiate between orthogonally defined categories and truly independent categories. Correlation results suggest only that two specific PSF groups have been observed together in the human error events analyzed in HERA. Correlations do not offer insight into why relationships exist among PSF groups. High correlation may indicate that the nodes are not orthogonally defined, that two nodes have a causal relationship, or that the nodes have a common parent or child node (see 5.3.2.3). High correlation may also indicate that the PSFs have a synergistic effect on error, i.e., they form part of an Error Context.

Error Contexts (ECs) are patterns of variance identified by factor analysis; each factor (eigenvector) retained forms one EC. Patterns of variance identified through FA are traditionally labeled “latent variables.” However, in this dissertation, these patterns are interpreted in a novel way. Since we are analyzing only human failure events (XHEs) from HERA and IDA, the observed patterns can be viewed as visible manifestations of the context underlying the error. This interpretation is justified for factors with eigenvalues greater than 1.0. An eigenvalue greater than 1.0 indicates that its eigenvector accounts for more than its proportional share of variance [102]. Each factor[3] is a group of PSFs that contributes more to human performance errors than would each PSF if acting alone; the whole (factor) is greater than the sum of its parts (PSFs).

PSFs with high correlation and no apparent causal relationship may be part of the same EC. Each EC is added to the model as a node. It is advisable to use different colors or shapes to differentiate between EC nodes and PSF nodes to reduce the likelihood of model misinterpretation. Arcs are drawn from each PSF to each EC with a factor loading $> |n|$. For our analysis $n = 0.3$; again this correlation cut-off value may be adjusted for different data sets. ECs can subsume some of the correlation-based arcs. The analyst should examine the arcs between PSFs that are also linked to the same EC. Arcs between PSFs may be removed if they are part of the same Error Context and the analyst determines that they have a weak causal

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[3] The number of factors retained varies, but one common rule is to retain only factors with eigenvalues greater than one. This is explained in more detail in 5.3.2.2

relationship.

5.2.4 Quantification

Model quantification entails populating a full probability table for each node. The methods used to convert correlation into conditional probability are discussed in Section 5.4.

5.3 Quantitative Analysis Techniques

5.3.1 Tetrachoric Correlation

To create the base structure of a model it is necessary to determine how the nodes of the model relate to each other. The relationships between the nodes in the model are determined based on the correlation of the PSFs. Correlation gives a quantitative measure of similarity between two variables – the amount of variance from the common area between them – thus garnering an initial understanding of the variable relationships. The degree of correlation is indicated by a number between -1 and 1. A correlation of 0 indicates complete independence between the variables, and a correlation of 1 indicates a perfect increasing linear relationship.

Several different correlation techniques can be used to develop a pair-wise correlation matrix. For normally distributed data, Pearson product moment correlations can be obtained using most commercial software packages. If data is not normally distributed, product-moment correlation values are not valid. Discrete data is not normally distributed, but the underlying process creating the data may be. For discrete data representing a latent continuous variable, polychoric correlation should be used [103, 104]. The fundamental assumption underlying polychoric correlation is that discrete data is representative of an underlying normally distributed model and that somewhere in the model there are thresholds where the variable changes states.

When using binary data such as the data from IDA and the HERA database, tetrachoric correlation, a specific case of polychoric correlation, should be used. Tetrachoric correlation cannot be used for binary data sets that violate the assumption of an underlying continuous distribution, as shown in Figure 5.3. One example is gender; gender is not normally distributed, a person is either male or female, and therefore tetrachoric correlation cannot be used on such data. However, most human behavior is not truly discrete and therefore so tetrachoric correlation is suitable for human behavior modeling.

In tetrachoric correlation the location of the threshold is estimated by applying a probit function to the data. The probit function is the inverse cumulative distribution function (cdf) of the standard normal distribution; it calculates the location of the threshold based on the amount of the curve to the left of the data [105]. It has been suggested that the continuity assumption underlying tetrachoric correlation is important, but the form of the underlying distribution is not necessarily restricted to a normal distribution due to the similarity between tetrachoric correlation and Item Response Theory [106, 107, 108]. The reader is referred to [100] for straightforward discussion of tetrachoric correlation and the requirements with regards to normality.

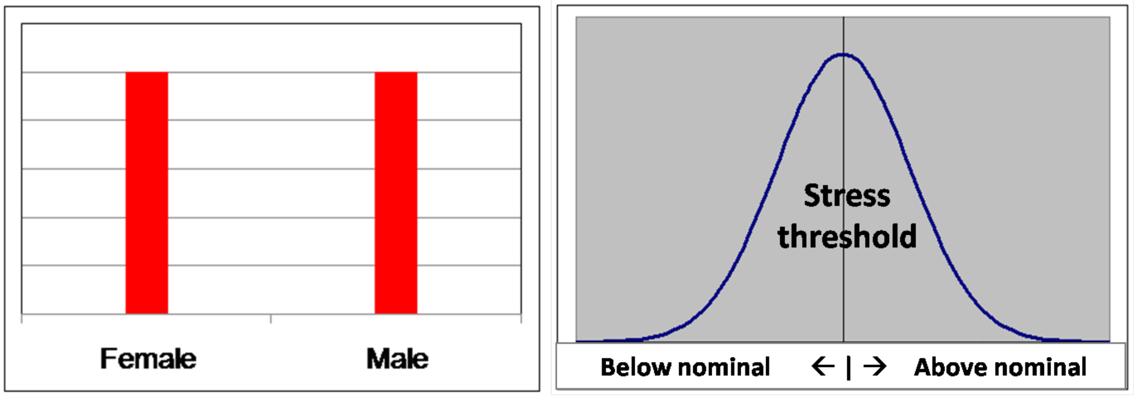

Figure 5.3: Two types of dichotomous measured variables. On the left is a graph of a truly discrete system. On the right there is a continuous variable which has been discretized based on the selected thresholde. Tetrachoric correlation can be used to analyze the data that produce the graph on the right, but is not suitable to analyze the data that form the graph on the left.

Determining tetrachoric correlation is a computationally intensive task. Polychoric and tetrachoric correlations can be calculated by using the %POLYCHOR macro for SAS [109] or the polychor option in the polycor package in R [110]. The polycor package can also be used to calculate polyserial correlation [111] between one discrete and one continuous variable.

5.3.2 Factor Analysis

Factor analysis can be used to discover relationships among multiple PSFs and between PSFs and error. The basic assumption of FA is that there are underlying influences in the data, and that these underlying influences manifest in patterns of variance that move together.

Factor analysis identifies underlying patterns (influence) and defines these patterns mathematically. For this reason it has been widely used in a number of fields for many years. According to Cattell [112] "its most valuable functions lie in the biological and behavioral sciences, where a great array of phenomena are multiply determined and where the conceptual independent variables are not easily located and agreed upon."

Broadly, FA is a family of multivariate techniques used to identify relationships among the variables and to identify underlying or latent influences. This is accomplished through evaluation of patterns of variance in the data. Variance is effectively a measure of deviation (variation) or spread of the data. In simple terms, variance is the difference between the values of individual data points and the mean of the data. In terms of human action, variance is the difference between observed behavior and expected or average behavior. Students typically examine the mean and standard deviation of test scores to determine an objective measure of their performance relative to classmates. The standard deviation is simply the square root of the variance of the test scores.

Exploratory FA can be used to analyze the structure of a set of variables; it is intended to be used for development of hypotheses about data. The theory behind exploratory factor analysis is that variance in the observed data is created not only by several measured variables, but also by invisible factors that impact the variables. That is, each variable is the linear combination of of its underlying individual influences [I] and a number of common influences [C], plus error (see Figure 5.4). The sum of these underlying factors results in the observable variable.

FA maps the original data onto a matrix of reduced size. The new matrix explains the same amount of variance as the original matrix, but the variance explained by each factor is greater than the variance explained by the original variables. The

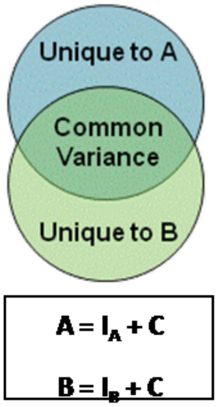

Figure 5.4: Exploratory FA treats each variable as the product of underlying individual influences [I] and communality (common influences) [C].

reader is referred to the references more detailed information and discussion of the many different FA methods [102, 113, 114].

For discrete data, such as that in the HERA database, a maximum likelihood (ML) approach is not recommended. The ML approach is likely to result in a matrix that is not positive definite because of the small sample size and the use of polychoric correlation. In our analysis we use the more robust Minres (MINimum RESiduals) technique [115]. The Minres FA technique is an unweighed least squares method that seeks to minimize the sums of squares of the residual matrix, so the suggested factors explain the maximum amount of variance in the correlation matrix. This is an iterative process wherein factors are estimated based on the initial communalities and the communalities are then updated based on the results and the process repeats.

5.3.2.1 Communality

Communality refers to the non-unique parts of a variable, or the amount of variance it has in common with other variables (center portion of Figure 5.4). This indicates how much of the construct's variance could be due to underlying factors, and sets the maximum possible amount of variance that can be accounted for by common factors. In exploratory factor analysis, communality estimates replace the (1.0) values along the diagonals of the correlation matrix. This replaces the perfect correlation each variable has with itself, with an estimate of the magnitude of the common influences affecting that variable.

Determining communality is not as straightforward as finding correlation values. An analyst must provide initial values and the FA can be run iteratively, with updated communality estimates provided from the prior iteration. There are several different ways to estimate initial communality values [102]. If iterative FA is used, the choice of communality value mainly affects the speed of model convergence.

5.3.2.2 Number of Factors

FA will provide n factors for an n x n correlation matrix. These factors will account for 100% of the variance in the sample, just as the original variables did. However, not all of these factors will be meaningful or capture a large percent of variance. Determination of the number of factors is as critical as developing the factors. Given the choice, it is preferable to err on the side of too many factors rather than too few, to reduce the chances of searching for relationships where there are none. Several different FA stopping rules have been proposed. The choice of stopping rule is subjective and is largely based on analyst preference. Popular stopping rules are introduced in the sections below. The best results are obtained by using several stopping rules and comparing the outcome.

The **Kaiser-Guttman rule** is one of the most popular techniques for determining the number of factors. It includes all factors with eigenvalues greater than 1. An eigenvalue is a property of linear transformation that indicates the amount of variance explained by a factor. An eigenvalue can be associated with each specific matrix or factor. An eigenvalue greater than 1 means that the factors accounts for more than its proportionate share of the original variance. The proportionate share of variance each factor is responsible for is determined by the factors loadings of its component variables.

In a **scree test**, the eigenvalues of the factors are plotted by factor number. The plot is examined for a discontinuity in the pattern. The idea behind a scree test is that important factors will have high eigenvalues (thus explaining relatively large amounts of variance); when the plot starts to level off we're left with residual variance due to error and random noise. Different sources argue that the factor at the cut-off point should or should not be included in the solution. It is important to look at the factor loadings and the interplay between the factors to determine which factors to keep. Ultimately the number of factors is decided by the analyst.

Parallel analysis is similar to the scree in test in that it assumes eigenvalues from data with underlying factors should be greater than eigenvalues from random data. Parallel analysis is performed by generating a matrix of random numbers equal to the size of the original set. The eigenvalues of the sample data and the random data are compared, and factors with eigenvalues greater than those observed in random data are retained.

5.3.2.3 Interpretation

Interpretation is the most critical step in any FA. An analyst must give meaning to the factors to transform them from abstract numerical concepts to meaningful constructs. There are numerous combinations of factor analysis techniques and FA stopping rules, and there is no single correct technique for any application. The correct technique is the one that produces the results that make the most sense. Analysts should explore several different factor models to determine which factors best fit their application. Without interpretation, the factors are simply patterns in data.

The first step in interpretation should be to examine the factor loading patterns, starting with the first factor. The first factor accounts for the most variance, the second factor accounts for the second most variance (i.e., of the remaining variance after subtracting the first factor) and so on. Analysts typically set their own minima based on data, but a commonly suggested rule is that only variables loaded above $|.40|$ on a factor should be included as part of that factor. When evaluating the factors it's equally important to consider what is in the factor as what is not.

In a data set there are several explanations for observed patterns of variance. Assuming that there is no overlap between any of the PSFs that would affect the

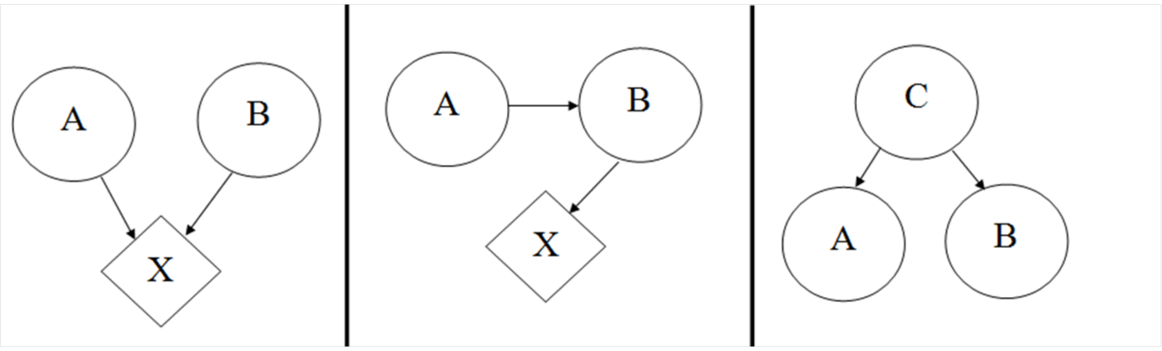

Figure 5.5: Possible causal relationships between two PSFs (A and B) and an outcome (X).

variance, all observed variance must be due to some kind of relationship between the PSFs. Figure 5.5 contains graphical representations of three potential causal relationships between PSF A, PSF B, and outcome X (i.e., error). In Figure 5.5a PSFs A and B are independent of each other, but they both directly influence the outcome; they have a common child node. In Figure 5.5b, PSF B directly influences the outcome, and PSF A indirectly influences the outcome through PSF B. In this relationship we expect to see the variance move together because A causes (or is a condition for) B. In Figure 5.5c A and B may or may not influence the same child node, but they still vary together because they share a parent node.

Interpretation of factor results provides preliminary groups of Error Contexts for specific work tasks. All sub-events used in this analysis are XHE events, i.e., known failures. We are adapting FA to interpret these underlying influences as visible manifestations of failure rather than invisible human performance. The pertinent information here is that use of FA will result in groups of PSFs that lead to human performance errors.

5.4 Assessment of BBN Model Parameters

While some experts suggest that quantification is should be postponed until the graphical structure of the model is considered robust [99], for HRA is it advisable to treat model quantification as part of an iterative approach to model development. A generic iterative model-development process consists of developing an initial framework, quantifying it, analyzing model fit, and refining probabilities, until resources run out or higher model accuracy cannot be obtained due to information limitations.

Given a well-populated database, conditional probability tables for the BBN can be developed automatically. In fact, both the network structure and the conditional probabilities can be automatically "learned" given sufficient data [97, 116]. Automatic quantification requires a large sample size and often imposes distributional assumptions on the data. Each variable relationship must be represented properly in the data sample; there cannot be missing data due to unobservable or infrequent variables [99]. Variables could be underrepresented in the data due to difficulty measuring them or limited opportunities to collect data on specific subsets; any missing values must be filled in by experts before automatic quantification can be realized [117, 118].

Assessment of conditional probability becomes more complicated when one must rely on a small sample with no information about some of the variables. There are few methodologies that specifically address how to quantify a BBN based on factor analysis results. We have identified two promising methods that can be used with HERA-style data to quantify the final model.

5.4.1 Regression Approach

Almond [119] provides guidance on how to transform factor analysis results into conditional probabilities. Almond suggests that it is possible to fully quantify a BBN using 2 matrices: a Q-Matrix to determine the graphical structure of the model and a correlation matrix to quantify the relationships in the model. The correlation matrix referred to is the matrix of correlations between variables and factors (the factor loadings). The Almond model is developed for the domain of educational testing, wherein latent proficiency (skills) are measured by performance on various tasks.

The Q-Matrix contains the relationships between the observable variables and the latent concepts in the model. It consists of columns representing different proficiency variables and row representing tasks. In a Q-matrix, each cell is assigned 1 or 0 with 1 indicating the task is relevant to the skill, otherwise the task is assigned 0. There is not a direct analog to proficiency test in the nuclear industry, but since the primary role of the Q-matrix is to determine the structure of the model, our tetrachoric correlation analysis is substituted for the Q-matrix. The matrix of factor loadings is used to quantify the model relationships among variables.

When comparing the Almond method to the HERA and IDA data, it is helpful to view “error context” as proficiency and “sub-event” as the task. The Almond model uses a set of observable tasks (e.g., student assessment tests) to predict the unobservable proficiencies of the student (e.g., aptitude for math). In our framework we use a set of observable tasks (sub-events) to predict the existence of unobservable error contexts.

There are four necessary inputs to be able to develop the model model:

- A set of variables (S) and latent factors (Y) to be included in the model.
- A set of marginal distributions P(S) for the variables S.
- A covariance matrix cov(Y).
- An estimate of the expected value of each factor μ_y of Y

Model quantification is achieved by developing a model regressing each node on its parents. The intercept and residual standard deviation in each regression is set to match the specified marginal distributions for the parent and child variables. The regression model is then discretized to form conditional probability tables.

5.4.2 Linear Equations

Bonafede and Giudici [120] suggest a set of equations that can be used to transform correlation values into joint or conditional probability tables. The approach was designed with the intention of reducing the number of conditional probabilities that must be assessed by experts by instead having them assess correlations, but it can be applied in situations where the correlations are calculated from limited data. We intend to utilize this to transform the tetrachoric correlations and the factor loadings into probability tables.

The method can be applied directly to quantify nodes with three or fewer parents. The method can be generalized for nodes with more than three parents, but the equation set becomes large due to the increasing number of possible interactions among parent variables. Bonafede and Giudici were able to place auxiliary nodes in their model to reduce the number of parent nodes using techniques suggested in Jensen [121]. If possible, it is suggested to reduce the number of parents by identifying independent groups of parents and splitting them from the others by inserting dummy nodes.

For nodes with independent parents, it is possible to calculate conditional probability ($P(A|B)$) directly by using the equations provided. For nodes with dependent parents it is necessary to calculate joint probabilities ($P(A \cap B)$) using the equations provided in this section; these can be easily converted into conditional probabilities.

The probability of the states of the variables is denoted as follows, where 0 denotes adequate and 1 denotes LTA:

For child C:	$P(C = 1) = c$	$P(C = 0) = 1 - c$
For parent X:	$P(X = 1) = x$	$P(X = 0) = 1 - x$
For parent Y:	$P(Y = 1) = y$	$P(Y = 0) = 1 - y$
For parent Z:	$P(Z = 1) = z$	$P(Z = 0) = 1 - z$

5.4.2.1 One Parent Case

For a BBN node C with a single parent X, the conditional probabilities can be assessed using the equations in Table 5.2. Since there are no correlations between parents, it is not necessary to use both sets of equations since($P(A \cap B) \times P(B) =$

$P(A|B)$.

The parameters k and M are defined as:

$k = \rho_{XC}\sqrt{Var(C)/Var(X)}$

$M = \sqrt{c(1-c)x(1-x)}$ where ρ_{XC} is the correlation between X and C.

Conditional probability	Joint probability
$\alpha_1 x + \alpha_2(1-x) = c$	$j_1 = \rho_{XC}M + xc$
$\alpha_1 - \alpha_2 = k$	$j_2 = c - \rho_{XC}M - xc$
$\alpha_1 + \alpha_3 = 1$	$j_3 = x - \rho_{XC}M - xc$
$\alpha_2 + \alpha_4 = 1$	$j_4 = 1 - c - x - \rho_{XC}M + xc$

Table 5.2: Equation systems for a child, C, with a single parent

Where the conditional probability α, or the joint probability c, is defined as:

		Parent	
		Yes	No
Child	Yes	α_1	α_2
	No	α_3	α_4

5.4.2.2 Two Parent Case

The two parent case is more complex because there may be correlation between both of the parents. For a case with two independent parents, the conditional probabilities can be calculated using the left side of Table 5.3. For a case where the parents are dependent, the joint probabilities can be calculated using the right side of Table 5.3.

The M parameters are:

$M_{CX} = \sqrt{c(1-c)x(1-x)}$

$$M_{CY} = \sqrt{c(1-c)y(1-y)}$$

$$M_{XY} = \sqrt{x(1-x)y(1-y)}$$

$$M_{CXY} = \sqrt[3]{c(1-c)x(1-x)y(1-y)}$$

and where:

	x	yes		no	
	y	yes	no	yes	no
c	yes	α_1	α_2	α_3	α_4
	no	α_5	α_6	α_7	α_8

5.4.2.3 Three Parent Case

The case for three parents is not as straightforward as for two parents because of multiple possible combinations of parental dependency. For the situations where all three parents are independent of each other, except that they have the same child, the conditional probability table is calculated using the equations on the left side of Table 5.4. However if any of the parents is dependent upon another parent, the equations on the right side of Table 5.4 must be used.

For the three parent case, the M parameters are defined as in the two parent case, and:

$$M_{XYZC} = \sqrt[4]{c(1-c)x(1-x)y(1-y)z(1-z)}$$

5.5 Summary of Model Building Procedure

This section summarizes the procedure for creating a quantified causal model of relationships among PSFs and Error Contexts in human error events. The pro-

Conditional probability (independent parents)	Joint probability (dependent parents)
$(\alpha_1-\alpha_2-\alpha_3+\alpha_4)xy+(\alpha_2-\alpha_4)x+(\alpha_3-\alpha_4)y+\alpha_4=c$	$j_1=\rho_{XYC}M_{XYC}+xyc+(\rho_{XC}M_{XC})y+(\rho_{YC}M_{YC})x+(\rho_{XY}M_{XY})c$
$(\alpha_1-\alpha_2-\alpha_3+\alpha_4)y+(\alpha_2-\alpha_4)=\frac{\rho_{XC}M_{XC}}{x(1-x)}$	$j_1+j_5=\rho_{YC}M_{YC}+yc$
$(\alpha_1-\alpha_2-\alpha_3+\alpha_4)y+(\alpha_3-\alpha_4)\frac{\rho_{YC}M_{YC}}{y(1-y)}$	$j_1+j_c=\rho_{XC}M_{XC}+xc$
$(\alpha_1-\alpha_2-\alpha_3+\alpha_4)=\frac{(\rho_{XYC})(M_{XYC})}{x(1-x)y(1-y)}$	$j_1+j_2=\rho_{XY}M_{XY}+xy$
$\alpha_2+\alpha_5=1$	$j_1+j_2+j_3+j_4=x$
$\alpha_2+\alpha_6=1$	$j_1+j_5+j_6+j_2=y$
$\alpha_3+\alpha_7=1$	$j_1+j_3+j_5+j_7=c$
$\alpha_4+\alpha_8=1$	$j_8=1-\sum_{i=1}^{7}j_i$

Table 5.3: System of equations used to calculate conditional probability from correlation and marginal probabilities for 2 independent parents (left) and 2 dependent parents (right)

Conditional probability (independent parents)	Joint probability (dependent parents)
$f(x,y,z) = (\alpha_1 - \alpha_2 - \alpha_3 + \alpha_4 - \alpha_5 + \alpha_6 + \alpha_7 - \alpha_8)xyz + (\alpha_2 - \alpha_4 - \alpha_6 + \alpha_8)xy + (\alpha_3 - \alpha_4 - \alpha_7 + \alpha_8)zy + (\alpha_5 - \alpha_6 - \alpha_7 + \alpha_8)zy + (\alpha_6 - \alpha_8)y + (\alpha_4 - \alpha_8)x + (\alpha_7 - \alpha_8)y + \alpha_8 = c$	$c_1 = \rho_{XYZC}M_{XYZC} + xcyz + \rho_{XYZ}M_{XYZ}c + \rho_{XYC}M_{XYC}z + \rho_{XZC}M_{XZC}y + \rho_{YZC}M_{YZC}x + \rho_{XY}M_{XY}zc + \rho_{XZ}M_{XZ}yc + \rho_{YZ}M_{YZ}xc + \rho_{XC}M_{XC}xc + \rho_{YC}M_{YC}xz + \rho_{ZC}M_{ZC}xy$
$\frac{\delta f}{\delta x} = \frac{(\rho_{XC})\sqrt{x(1-x)c(1-c)}}{x(1-x)}$	$c_1 + c_2 + c_3 + c_4 + c_5 + c_6 + c_7 + c_8 = z$
$\frac{\delta f}{\delta y} = \frac{(\rho_{YC})\sqrt{y(1-y)c(1-c)}}{y(1-y)}$	$c_1 + c_2 + c_3 + c_4 + c_9 + c_{10} + c_{11} + c_{12} = x$
$\frac{\delta f}{\delta z} = \frac{(\rho_{ZC})\sqrt{z(1-z)c(1-c)}}{z(1-z)}$	$c_1 + c_2 + c_5 + c_6 + c_9 + c_{10} + c_{13} + c_{14} = y$
$\frac{\delta^2 f}{\delta x \delta y} = \frac{(\rho_{XYC})\sqrt[3]{x(1-x)y(1-y)c(1-c)}}{x(1-x)y(1-y)}$	$c_1 + c_3 + c_5 + c_7 + c_9 + c_{11} + c_{13} + c_{15} = c$
$\frac{\delta^2 f}{\delta z \delta y} = \frac{(\rho_{YZC})\sqrt[3]{z(1-z)y(1-y)c(1-c)}}{z(1-z)y(1-y)}$	$c_1 + c_2 = \rho_{XYZ}M_{XYZ} + xcy + \rho_{XY}M_{XY}z + \rho_{XZ}M_{XZ}y + \rho_{YZ}M_{YZ}x$
$\frac{\delta^2 f}{\delta x \delta z} = \frac{(\rho_{XZC})\sqrt[3]{z(1-z)x(1-x)c(1-c)}}{x(1-x)z(1-z)}$	$c_1 + c_9 = \rho_{XYC}M_{XYC} + xcy + \rho_{XC}M_{XC}y + \rho_{YC}M_{YC}x + \rho_{XY}M_{XY}c$
$\frac{\delta^3 f}{\delta x \delta z \delta y} = \frac{(\rho_{XYZC})\sqrt[4]{z(1-z)y(1-y)c(1-c)x(1-x)}}{x(1-x)y(1-y)z(1-z)}$	$c_1 + c_3 = \rho_{XZC}M_{XZC} + xcy + \rho_{XC}M_{XC}z + \rho_{ZC}M_{ZC}x + \rho_{XZ}M_{XZ}c$
$\alpha_1 + \alpha_9 = 1$	$c_1 + c_5 = \rho_{YZC}M_{YZC} + xcy + \rho_{YC}M_{YC}w + \rho_{ZC}M_{ZC}y + \rho_{YZ}M_{YZ}c$
$\alpha_2 + \alpha_{10} = 1$	$c_1 + c_2 + c_9 + c_{10} = \rho_{XY}M_{XY} + xy$
$\alpha_3 + \alpha_{11} = 1$	$c_1 + c_2 + c_3 + c_4 = \rho_{XZ}M_{XZ} + xz$
$\alpha_4 + \alpha_{12} = 1$	$c_1 + c_3 + c_9 + c_{11} = \rho_{XC}M_{XC} + xc$
$\alpha_5 + \alpha_{13} = 1$	$c_1 + c_2 + c_5 + c_6 = \rho_{YZ}M_{YZ} + yz$
$\alpha_6 + \alpha_{14} = 1$	$c_1 + c_3 + c_5 + c_7 = \rho_{ZC}M_{ZC} + zc$
$\alpha_7 + \alpha_{15} = 1$	$c_1 + c_5 + c_9 + c_{13} = \rho_{YC}M_{YC} + yc$
$\alpha_8 + \alpha_{16} = 1$	$c_{16} = 1 - \Sigma_i^{15} c_i$

Table 5.4: Equation systems for a child, C, with three parents

cedure can be modified to create a mixed expert/data model by applying step 1 to identify which variables can be included quantitatively and using expert information to augment the model.

The current methodology assumes that PSFs have two states (Adequate vs. Less Than Adequate (LTA)) because this is the form of current data. Given additional levels of discretization, the methodology will start by identifying and merging similar PSF states (e.g. totally inadequate, partially inadequate) for each PSF and then proceed to identifying and merging similar PSFs. Suggested threshold values are based on the currently available data and may be adjusted as additional data becomes available.

1. **Determine which PSFs [4] will be included in quantitative analysis.**
    (a) Start with the expanded PSF hierarchy (Table 3.2) and collapse the PSFs:
        i. Identify PSFs that are LTA in fewer than 10% of the sub-events. Merge these PSFs with one or more PSFs at the same level of the hierarchy, or collapse the category.
        ii. Identify PSFs that are LTA in greater than 90% of the sub-events. Expand these PSFs into one or more sub-levels.[5]

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[4] For the sake of brevity, the terms "PSFs" is used to represent all elements in the hierarchy (i.e., PSFs and behaviors/metrics)

[5] For PSFs that cannot be expanded based on the current structure, the structure will need to be modified by identifying additional additional metrics or behaviors or by adding sub-levels of the PSF.

    iii. Run correlation analysis on PSF set. Identify outliers (PSFs producing several correlations $> |0.95|$). Merge with one or more PSFs.
    iv. Run factor analysis on PSF set. Identify PSF producing the largest Heywood case and merge with one or more PSFs. Repeat this step until all Heywood cases are eliminated.

2. **Draw directed arcs between PSFs with (correlations $> |0.3|$).**[6]
   (a) Direction of the arc is based on expert information about the direction of causality.
   (b) Arcs may be omitted between the PSFs if the correlation is judged to be the result of parent, child, or EC relationships in the model.

3. **Identify ECs and draw arcs between PSFs and ECs**
   (a) Run several FA models on PSF set.[7]
   (b) Apply FA stopping criteria to determine appropriate number of factors.
   (c) Include each factor as an EC in the final model. Draw arcs from each PSF included in the factor to the EC node.

4. **Populate marginal and conditional probability tables.**
   (a) Use methods suggested in Section 5.4 or use direct expert elicitation.

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[6] Appendix C provides R code for calculating tetrachoric correlations using the polycor package.

[7] Appendix C provides R code for Principal Axes and Minres factor models ranging from 1-5 factors.

Chapter 6

PSF Model Development and Insights

This chapter presents a set of models that were developed using the methodology introduced in Chapter 5. Three different models were created to demonstrate the flexibility of the methodology and its ability to meet different research goals. The models include a high level (“6-Bubble”) model for the major aspects of the socio-technical system, a Mixed Expert and Data Model (“MEDM”) with interactions among over 30 of the PSFs and behaviors, and a quantified (“9-Bubble”) model that contains a reduced set of PSFs linked to Error Contexts. The 6-Bubble model was created to maximize insight gathered from the data. The model was formed by aggregating all of the data to produce the most statistically significant results possible from the current data. The MEDM was created to display causal relationships among the full set of PSFs and to demonstrate how the methodology can be used to combine expert judgment and data into one model. The 9-Bubble model was created to provide a quantitative model of the relationships among PSFs and to link the PSFs to error; this model form is intended for use in HEP calculations.

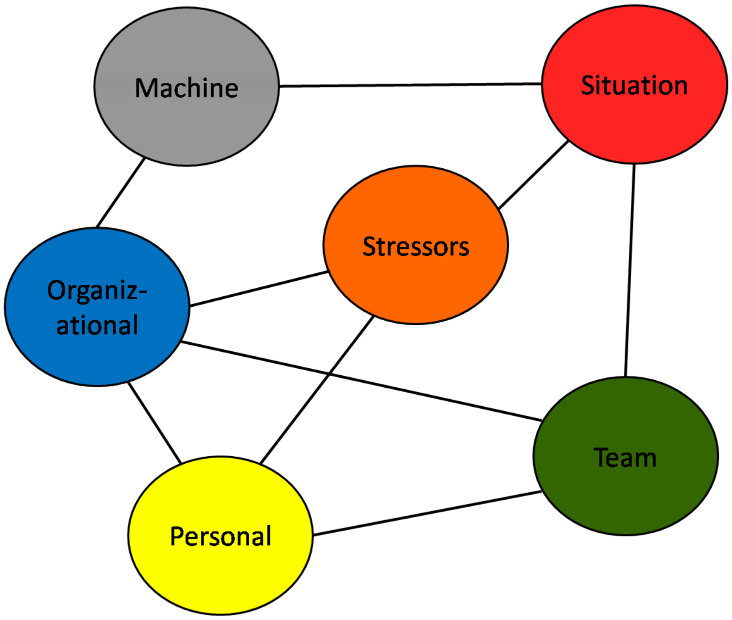

Figure 6.1: The interactions among the six aspects of the socio-technical system.

6.1 6-Bubble Model

The 6-Bubble Model contains the six major elements of the socio-technical system. The 6-Bubble Model is presented in Figure 6.1; for this model, the hierarchy was collapsed into the 6 top level groups. Lines are based on expert information from the US NRC Workshops [44]. There are sufficient data to make statistically valid conclusions about the 6-Bubble model, although under-representation of certain factors in HERA leaves considerable room for error in the analysis. We ran both tetrachoric correlation and factor analysis on the six PSF groups. However only correlation results are presented here because the FA did not converge for any factor model with fewer than six factors. This suggests that the six PSF categories are generally independent, as expected.

Table 6.1 displays the tetrachoric correlation coefficients among the six PSF

	Machine	Team	Organization	Situation	Stressors	Personal
Machine	1					
Team	-0.06	1				
Organization	-0.06	-0.21	1			
Situation	0.35	0.47	0.06	1		
Stressors	-0.15	0.42	-0.13	0.19	1	
Personal	-0.10	0.31	0.07	0.10	0.32	1

Table 6.1: Correlations among the high-level PSFs. The results suggest that the groups are largely orthogonal and independent, with some exceptions discussed in the text.

groups. Correlation values below |0.30| suggest that the PSFs tend to be independent in the data. Definitional orthogonality is one of the necessary aspects that defines independence, so the number of low correlations observed suggest that the 6-group PSF framework is orthogonally defined for the majority of the categories. Five of the correlation values are large enough to merit further discussion: Machine–Situation, Team–Situation, Team–Stressors, Team–Person, and Stressors–Person.

The stressor PSFs are largely based on personal perception, and the person-based PSFs play a significant role in the way that individuals perceive loads. This close relationship ensures correlation between the two PSF categories. However, the stressor and person categories can still meet the condition for definitional orthogonality; the PSFs in the categories may interact, but they are distinctly defined entities.

The team-based PSF category has a non-trivial correlation with several other PSF categories. There are multiple explanations for this behavior. Team factors are likely to be correlated with the person-based factors because a team is composed of individuals, and therefore the individual characteristics of the team members affect the team. For example while communication is categorized as team-based, each member has a unique inherent personal communication style, and these styles combine together to form the team-based communication. However, we can state that by definition the communication must occur between two or more people, so while the inherent characteristics of each person do play a role, there cannot be communication without multiple individuals, i.e., a team. It follows logically that there is a correlation between team-based and stressor factors because personal characteristics influence both elements.

The high correlations between team-based factors and other PSF categories may also be an indicator of the strong role that teams play in commercial nuclear power. For most operations and maintenance tasks there is either direct teamwork or some level of review to ensure that tasks are completed correctly. The team has a significant role in almost every aspect of commercial power and it is natural that the team would correlate with many aspects of the socio-technical system.

The highest correlation observed is between team-based factors and situation-based factors. It is important to note that the data included only human error events that had an impact on the plant, i.e., the correlation between human error and the values in Table 6.1 is 1.0. During normal operating conditions the operating crew plays a generally passive role, monitoring indicators of the system state. However, during abnormal situations the crew shifts to an active role in controlling the plant. The data suggest that poor teamwork alone is not sufficient to produce an error. This is logical because humans do not have the opportunity to make an error that impacts the plant if they are not affecting the state of the plant. Team-based factors may have a significant influence on human performance, but they do not become important to the plant until the team is asked to interact with the plant. The high correlation between the machine-based factors and situation-based factors can be explained in a similar way. The machine design does not become salient until a situation requires personnel to interact with the machine.

6.2 Mixed Expert/Data Model

The Mixed Expert and Data Model (MEDM) includes nodes and relationships based on both data and expert opinion. The model is presented as Figure 6.2 The data-derived part of the model is based on results from tetrachoric correlation analysis. The goal was to include all of the second-level PSFs and several third-level PSFs and behaviors/metrics from the PSF hierarchy (see Chapter 4) in the model. The procedure presented in Section 5.2 was modified to exclude factor analysis because the data set was too small to permit factor analysis on a large variable set. The iterative process of running quantitative analysis, examining results, and refining the PSF set was performed, but the quantitative analysis was limited to tetrachoric correlation.

A correlation table containing the reduced PSF set is presented as Table 6.2. Some of the correlations produced among the full set PSFs were erroneous (as large as |0.999|) and were removed from the table. A correlation of |0.999| is so close to

|1.0| that one must be suspicious of the results. Many of the PSFs with correlations of |0.999| also had numerous correlations above |0.8|, which suggests that there were not sufficient data to produce valid results for the PSF. A review of the data used to create the correlation table found that the PSFs exhibiting erroneously high correlations were all PSFs that occurred in fewer than 10% of the events. Each of these PSFs was removed from the quantitative analysis.

The PSFs in Table 6.2 became nodes in the data-based portion of the model. In Figure 6.2, these PSFs are represented by nodes with a solid border. PSFs that could not be included in the quantitative analysis due to data limitations are included as nodes with a dashed border.

Causal relationships between nodes are indicated with arrows. Solid arrows were drawn between nodes when correlation exceeded |0.3| and the experts determined that a causal relationship could exist between the nodes. Arrows were not drawn between PSFs with correlations exceeding |0.3| when the experts determined that there was not a causal link. Dashed arrows were drawn between PSFs that have a causal relationship according to the experts, but which did not correlate in the quantitative analysis. Relationships among the dashed nodes and between the dashed nodes and solid nodes were developed by experts and are therefore represented by a dashed arrow. Several dashed nodes have solid arrows pointing to a child node; these nodes have a logical relationship by definition. One example is *Procedure Quality* to *Procedures*; a solid arc was created between them because by definition the quality of the procedures is one aspect of the adequacy of the procedures in general. The child node completely encompasses the parent node by definition.

Some behavioral indicators and other metrics were included in the model as rectangles. The included metrics are not designed to be comprehensive; they are included only to demonstrate how metrics fit into the model. The behaviors and metrics can be observed more easily than the associated PSFs. For example, a supervisor can observe the compliance behavior of a worker more easily than the attitude of the worker. In a quantified BBN, the goal is to set evidence (observe the state of one or more nodes) and see how the evidence affects the rest of the model. The metrics/behaviors offer a more concrete, observable factor for invisible processes, which helps different analysis set evidence more uniformly and thus increases analysis reproducibility. Likewise, a utility may not be able to identify a problem with everything encompassed by the word *Staffing*, but the utility can observe situations where an inadequate number of personnel were assigned to a task.

6.3 9-Bubble Model

6.3.1 PSF Set

Our original intention was to develop a large model containing all of the PSFs in the second and third levels of the hierarchy. However, due to limited data we were unable to produce valid, convergent factor analysis results on the entire PSF set. The set of PSFs used in the model was developed by using the procedure for collapsing

	HSI/System Responses	Task Load	Time Load	Knowledge/Skills	Direct Supervision	Hardware & Software Conditions	Complex	Perceptions	Communication	Team Coordination	Training	Safety Culture	Management	Resources	Attention	Morale/Motivation/Attitude
HSISys	1.00															
TaskLoad	0.24	1.00														
TimeLoad	0.36	0.53	1.00													
KnowSkill	-0.05	0.01	0.04	1.00												
DirSuper	-0.24	0.27	0.02	0.18	1.00											
CondEvent	0.50	0.18	0.28	-0.25	-0.34	1.00										
Complex	-0.01	0.37	0.50	0.16	0.39	0.18	1.00									
Percept	0.19	0.05	0.55	0.03	0.24	-0.17	0.28	1.00								
Comm	0.26	0.39	0.28	-0.27	0.18	0.00	0.22	0.19	1.00							
TeamCoor	0.19	0.30	0.25	-0.37	0.24	0.54	0.13	0.34	0.19	1.00						
Training	0.09	0.25	0.19	0.05	0.40	-0.17	0.42	0.74	0.09	0.16	1.00					
SftyCulture	-0.27	-0.25	-0.25	0.11	0.16	-0.43	-0.36	-0.02	-0.07	-0.50	0.05	1.00				
Mgmt	-0.09	-0.10	-0.17	-0.09	0.17	-0.38	0.08	0.24	0.42	-0.16	0.37	0.34	1.00			
Resources	-0.03	0.10	0.04	-0.13	0.03	0.00	0.36	0.19	0.05	0.12	0.27	-0.06	0.22	1.00		
Attention	-0.43	0.65	0.05	0.05	0.16	-0.15	0.00	-0.10	0.08	0.02	0.18	0.02	-0.04	0.18	1.00	
MMA	-0.00	-0.03	-0.05	-0.50	-0.04	0.20	-0.15	-0.08	0.15	0.08	-0.13	0.21	0.08	-0.00	-0.10	1.00

Table 6.2: Tetrachoric correlation table for the new set of PSFs.

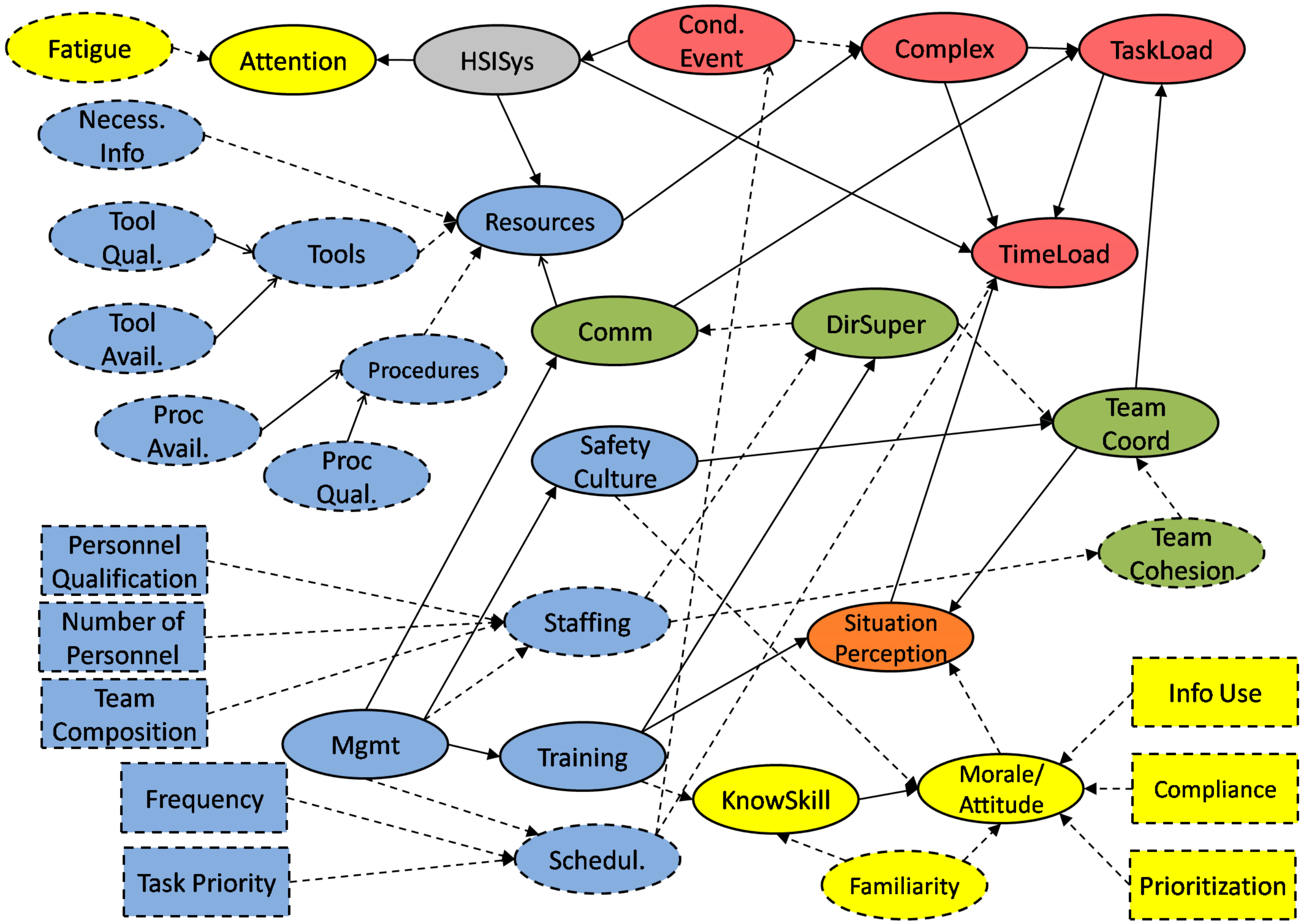

Figure 6.2: The Mixed Expert/Data Model. Solid ovals are PSFs included in the quantitative analysis. Ovals with a dashed border are PSFs that could not be included in the quantitative analysis. Solid arrows denote relationships that are supported by both quantitative analysis and expert judgment. Dashed arrows denote relationships that are supported only by expert judgment. Dashed nodes with solid arrows leading to another node are logical relationships. Rectangles are behavioral indicators or other observable metrics that can be used to assess the state of the PSF. The colors indicate which PSF group the node is in. Gray corresponds to machine-based PSFs; red to situation-based; orange to stressor-based; yellow to person-based; blue to organization-based; and green to team-based.

Model Node	Included PSFs
Training	Training
Org. Culture	Safety Culture, Management Activities, Corrective Action Program
Resources	Procedures, Tools, Necessary Information
Team	Communication, Team Coordination, Team Cohesion, Direct Supervision, Role Awareness
Attitude	Morale/Motivation/Attitude, Bias, Attention
Knowledge	Skills, Knowledge and Experience, Familiarity with Situation, Physical & Psychological Abilities
Machine	Human-System Interface, System Responses
Loads/Perceptions	Task Load, Time Load, Other Loads, Perceived Situation Severity, Perceived Situation Urgency, Perceived Decision Responsibility
Complexity	Task Complexity, Hardware & Software Conditions

Table 6.3: The 9 PSFs used in the final causal model

the hierarchy, discussed in Section 5.2. In order to retain information from the data, PSFs were merged together instead of completely eliminated whenever possible.

The final PSF set contains the 9 elements that had sufficient data to be included in the model and that provided convergent factor groupings with correlations below $|1.0|$. The correlations among these 9 PSFs are suitable to quantify a causal model, and the factors output by FA are also suitable to be included in the model. The PSF set is presented in Table 6.3. The remainder of Section 6.3.1 provides justification for merging PSFs to create the 9 PSF set.

Training had sufficient data to be retained as a PSF and no other PSFs were merged with it.

Staffing, *Scheduling*, and *Compliance* were collapsed into *Management Activities*. The *Management Activities* PSF was then merged with *Safety Culture* and

Corrective Action Program to form one PSF for organizational attitude/culture. Both *Management Activities* and the *Corrective Action Program* demonstrate how the highest members of the organization set priorities. These behaviors demonstrate the management attitude toward *Safety Culture*. *Safety Culture* becomes visible in additional ways throughout the plant, but the safety message comes from the top.

Procedures, *Tools*, and *Necessary Information* were merged into the *Resources* PSF. Different resources tend to be more relevant in different plant tasks (e.g., tools are typically used in maintenance tasks), but the resources serve the same purpose. In many control room situations the procedures are the "tool" required. Most resources are provided by the organization, although necessary information can be provided by other team members (e.g., logbooks). However given data limitations we chose to treat all of the resources as an organizational PSF because the majority of data pointed to organizational responsibility for resources.

The *Team* PSF is comprised of *Direct Supervision, Role Awareness, Communication, Team Coordination*, and *Team Cohesion*. *Role Awareness* was merged with *Direct Supervision* because the majority of HERA events where role awareness was an issue involved inadequate role awareness on the part of the direct supervisor. This can be seen in the HERA analysis [62]:

> The onsite and operations managers were above the shift managers, and it seems that they were too involved in what was going on, assuming responsibility that they should not have. It is inferred that the roles and responsibilities of each

> person were poorly understood by those involved.

and also in HERA analysis [66]:

> The SNSS was too involved in trying to restore CW pumps to be able to maintain his oversight and advisory roles.

Morale/Motivation/Attitude, *Bias*, and *Attention* were combined into the *Attitude* node in the model. Biased behavior or intentional inattention can be an indicator of a worker's underlying attitude. Bias can also result in improperly assigning attention. In retrospective analysis it is often difficult to differentiate between lack of attention and intentional disregard of certain information. The personal behaviors *Compliance, Prioritization, Information Use*, and *Task Order* are used as metrics of *Attitude*.

Skills, Knowledge & Experience, and *Physical & Psychological Abilities* were combined into the *Knowledge* PSF, because all three PSFs refer to the internal resources available to each individual. *Familiarity with Situation* was also included in this node because familiarity is partially the result of increased experience.

HSI was combined with *System Responses* to form the *Machine* PSF. Both PSFs relate to how the human perceives and interacts with the machine; *HSI* refers to the physical system design whereas *System Responses* refers to the person's mental model of the system. There were no other PSFs suitable to be merged with *HSI* or *System Responses*. These PSFs were particularly underrepresented in the data, in part due to the difficulty of assessing them from LERs.

Other Loads was combined with *Task Loads* because in most retrospective analyses it is difficult to distinguish between task and non-task loads. The idea of task vs. non-task is depends on which task a person is “supposed” to be completing at the moment. It is especially difficult to differentiate between these loads in situations where personnel are expected to complete multiple tasks at once. *Task Load* was combined with *Time Load* and *Other Loads* because all three PSFs represent aspects of the stressors affecting the worker. *Perception of Urgency*, *Perception of Severity*, and *Perception of Decision Impact* were initially merged into *Perception of Situation*. Since *Perception of Situation* acts as a stressor it was combined with the loads to form the *Loads/Perceptions* node.

Hardware & Software Conditions was merged into *Complexity* because degraded machine conditions tend to increase the complexity of a scenario

Environment could not be included in the analysis individually and did not sufficiently correlate with other PSFs to be combined with any other PSFs.

6.3.2 Quantitative Analysis

After reducing the set of PSFs to a set that produced convergent factor analysis results with correlations below $|1.0|$, we examined the correlations to determine which PSFs could be further combined. The correlation table is presented in Table

	Training	Org. Culture	Resources	Team	Attitude	Knowledge	Machine	Loads/Perceptions	Complexity
Training	1								
Org. Culture	0.151	1							
Resources	0.274	0.029	1						
Team	0.373	-0.025	0.094	1					
Attitude	0.036	0.152	0.006	0.094	1				
Knowledge	0.042	-0.116	-0.086	-0.073	-0.434	1			
Machine	0.089	-0.384	-0.029	0.179	0.004	0.072	1		
Loads/Perceptions	0.514	-0.254	0.17	0.449	0.305	0.076	0.319	1	
Complexity	0.331	-0.319	0.343	0.354	0.082	0.100	0.205	0.463	1

Table 6.4: Tetrachoric correlation values used to develop the structure of the 9-Bubble Model

6.4. The raw data used to create this model are included as Appendix D

There are some correlations that cannot be explained by a causal relationship between the PSFs. For example, *Complexity* shows high correlation with *Team.* To explore these relationships, we ran several exploratory factor analyses on the 9 PSFs and compared the results. The analysis results shown in Table 6.5 are the output of an unrotated, Minres factor analysis. This selection was made because Principal Factor Analysis (PFA) produced results with factors with correlations exceeding |1.0| for some PSFs. Minres factor analysis is an iterative process that develops the factors by minimizing the sums of squares of the residual matrix.

We ran PFA and Minres factor models for between 1 and 5 factors. We selected the 4 factor model based on the eigenvalues of the resulting factors and the shape

Table 6.5: Factor analysis results for the 9 PSF groups

	EC1	EC2	EC3	EC4
Training	0.67			
Org. Culture		0.75	−0.65	
Resources				0.98
Team	0.54			
Attitude		0.74	0.64	
Knowledge		−0.37		
Machine				
Loads/Perceptions	0.72		0.45	
Complexity	0.41		0.35	0.34
Eigenvalues	2.58	1.63	1.27	0.98

of the scree plot. The screen plot showed discontinuity after the fourth factor. For the PFA, the first four factors had eigenvalues greater than 1.0. The fourth factor in the Minres results has an eigenvalue of 0.98, but we elected to retain this factor based on the scree plot and the PFA eigenvalues. In both PFA and Minres FA, the four-factor model had a highest p value of the five models tested.

When interpreting the factors, the order of the factors is important. Factor 1 explains the most variance. Factor 2 explains the most variance when the variance explained by factor 1 is removed, and so on. This makes the first factor the most important/significant factor in the data. These factors are interpreted as Error Contexts (ECs)

6.3.3 Model Structure

The model contains a node for each PSF and each EC. Arcs were drawn between PSFs with correlations above $|0.3|$ with a causal relationship supported by

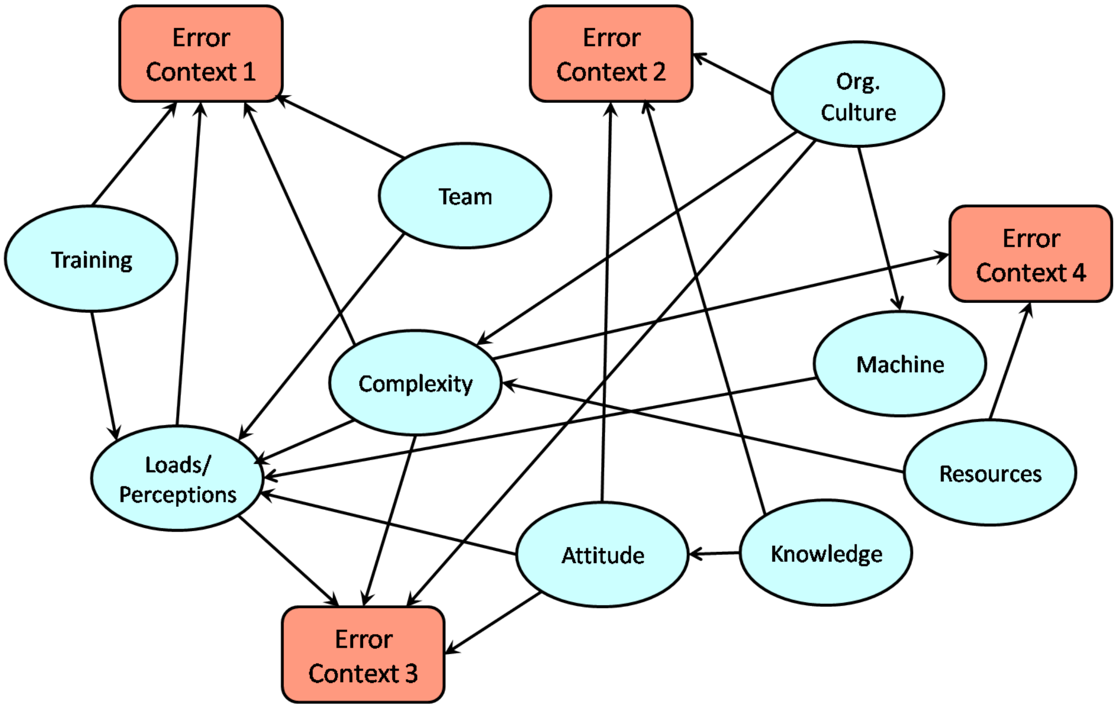

Figure 6.3: The “9-Bubble” model

expert information. Relationships that can be explained causally are explained in this section. Relationships that do not have an obvious causal link are explained in Section 6.3.4. The model is presented as Figure 6.3.

There are numerous causal arcs into *Loads/Perceptions*. There are high correlations between *Loads/Perceptions* and *Training, Team, Machine, Complexity*, and *Attitude*. Each of these correlations has been interpreted as a causal contributor to *Loads/Perceptions* because they all directly affect the way personnel perceive the situation. This is because perceptions and loads are the worker's personal assessment of the scenario, including the machine, the team, and the situation. Intrinsic worker attitude also causally contributes to the individual's loads and perceptions because the characteristics that manifest as attitude also affect individual perception.

The causal arrow from *Knowledge* to *Attitude* represents a negative correlation. The arrow implies that adequate knowledge contributes to less than adequate personal attitudes, or that LTA knowledge contributes to adequate attitudes among personnel. This can be seen in situations where experienced personnel use work-arounds (non-compliant attitude) to deal with a situation. Less experienced personnel may not know as much about the system and therefore may not be able to develop work-arounds for the system. They must rely on available resources and tend to approach a situation more cautiously to compensate for their reduced knowledge.

This effect is observed in HERA event [76], where an experienced worker violated emergency operating procedures that require reporting system state to the US NRC:

> The shift supervisor relied on his memory of determination/notification requirements rather than check any procedure ([76], XHE8).

A less experienced worker may have avoided making this error, because LTA knowledge about the situation would force the worker to consult the procedure.

The causal arcs from *Organizational Culture* to *Machine* and from *Organizational Culture* to *Complexity* represent a negative correlation. The negative correlation here could be partially due to the effect of safety culture on the HERA data; organizations with good *Organizational Culture* tend to be more willing to report problems with the machine or may more accurately report the complexity of a situation. So the causal arrow in the model does not necessarily imply that adequate *Organizational Culture* causes inadequate machinery or complexity, rather that adequate *Organizational Culture* causes increased reporting of inadequate machinery and complex situations. Additionally, organizations with inadequate machinery must be more attentive to the machinery and thus benefit from a positive organizational culture. As additional data becomes available, further analysis should be done to determine the nature of the relationships indicated by these links, or if this link is the result of underrepresentation of machine factors in the data.

The causal arrow from *Resources* to *Complexity* is logical, because lack of resources results in additional complexity. This can be seen in situations where there are inadequate procedures. Inadequate procedures may contribute to complexity in several ways. When there are no procedures for a situation, the required actions are knowledge based. Knowledge-based actions are more complex than rule-based actions. Extremely complex situations are also more likely than routine situations to be outside the scope of procedures. However, we cannot draw a causal arrow from resources to complexity based on this logic, because the complexity of the situation doesn't necessarily cause the lack of procedure.

6.3.4 Error Contexts

The first error context is the set of *Training, Team, Loads/Perceptions*, and *Complexity*. The PSFs contributing to this EC have the most significant impact on error because this is the most significant. The first factor's eigenvalue is much larger than the eigenvalues of the other factors; it accounts for the greatest amount of variance in the sample. The relationships among these PSFs suggest several things about how errors occur in NPPs. The inclusion of *Hardware & Software Conditions* (merged into the *Complexity* node) as one of the contributors is significant since humans typically do not have the opportunity to commit an error if they are not interacting with the plant. During normal operating conditions the plant operates with minimal human intervention. Operators monitor plant conditions until an abnormal occurrence, i.e., a conditioning event, that requires the operating crew or maintenance personnel to interact with the plant.

The relationship between *Hardware & Software Conditions* and *Complexity* is a causal relationship – a degraded machine state typically causes the situation to become more complex. One example of a conditioning event increasing situation complexity can be seen in [122], where an EDG trip occurred during a LOOP event. Other influences that affect *Complexity* include *Teamwork* and *Training*. A well-functioning team can reduce the perceived loads and the situation complexity by efficiently organizing and dividing tasks. Training can contribute to the proper functioning of the team and also contributes to personnel knowledge, which affects how a person perceives the load and the complexity of the situation.

The second error context is *Organizational Culture, Attitude*, and *Knowledge.* The LTA states of *Organizational Culture* and *Attitude* are positively correlated with the EC, and LTA *Knowledge* is negatively correlated with it. This suggests that LTA *Knowledge* is not a contributor to this "type" of error. Rather there is not inadequate knowledge; we can't say that the people are particularly knowledgeable, but they do not lack necessary knowledge. The combination of adequate *Knowledge* with LTA *Attitude* suggests that the attitude of the worker plays a major role in errors committed by experienced personnel. The data support the theory that workers with less knowledge or experience tend to compensate for their inexperience by working more carefully. Experienced personnel are prone to making mistakes due to carelessness or poor work practices, including compliance and prioritization behaviors. Poor work practices are rarely limited to one member of an organization; rather, LTA *Organizational Culture* creates an environment that allows worker attitudes to decline.

The third error context is *Organizational Culture, Attitude, Loads/Perceptions*, and *Complexity.* The fact that both *Loads* and *Complexity* load on this factor is logical – a more complex situation will increase perceived loads. Likewise, the number of simultaneous tasks (actual loads) can also increase complexity. *Attitude* plays a role in how situations, especially complex situations, are translated into perceived loads. *Organizational Culture* has a negative correlation with this PSF, which suggests that this factor is linked to adequate organizational culture. This is likely because the second error context (which has a higher eigenvalue and thus explains more of the variance) absorbs most of the situations where *Organizational Culture* is LTA.

The fourth error context is *Resources* and *Complexity.* This is the least important factor, which suggests that inadequate resources are not seen alone in many errors. Again this EC is linked to *Complexity*, which is logical because complex situations may be unfamiliar to personnel and thus personnel rely on the resources, especially procedures, more heavily.

To summarize, the first error context is created by the combination of LTA *Team* and *Hardware & Software Conditions*. LTA *Training, Loads/Perceptions*, and *Complexity* PSFs are included in this error context because they are causally linked to the conditioning events and the team. The second error context is adequate *Knowledge*, LTA *Attitude*, and LTA *Organizational Culture* (which allows the LTA attitude to exist). The third error context is a combination of LTA *Attitude, Loads*, and *Complexity*; it most applicable in situations where *Organizational Culture* is adequate. The fourth error context is LTA *Resources* and *Complexity.*

HSI does not loan on any of the factors and therefore does not appear in an error context. This is logical because of the generally unchanging nature of HSI; workers accept the system as it is designed. Operators tend to compensate for system shortcomings, e.g., they develop workarounds to deal with bad display. Maintenance workers also develop workarounds, e.g., a worker who must enter a narrow space between display panels might turn sideways to avoid bumping into a panel.

The quantitative analyses support many relationships already theorized to exist. It is interesting to note that *Complexity* loads on the first, third, and fourth factors, which suggests that complexity is an important contributor to human error. Complex situations may include failures of multiple system components, failure masking (e.g., failed sensors that obscure hardware failures), and unanticipated plant conditions. These complex situations may be outside the scope of worker training and available procedures, so worker behavior shifts from rule-based to knowledge-based, which increases the likelihood of error.

6.3.5 Model Parameters

Conditional probability tables were developed for the 9-Bubble Model by applying the appropriate equations from Section 5.4.2. All of the probabilities are conditional on the error and a risk significant scenario (RSS),

$$P(PSFs|(Error \cap RSS))$$

Marginal probabilities for each PSF were determined from the 158 XHE events used in the analysis. Using the data provided in Appendix D, the marginal probability of each state (k) of PSF i was assessed using the relative frequency of the state:

$$P(PSF_i = k) = \frac{n_k}{n} \tag{6.1}$$

for n sub-events.

For root nodes, the marginal probabilities fully specify the conditional probability table. The conditional probability tables for the five root nodes are below.

Training	LTA	0.37
	Adequate	0.63

Org. Culture	LTA	0.48
	Adequate	0.52

Resources	LTA	0.40
	Adequate	0.60

Team	LTA	0.46
	Adequate	0.54

Knowledge	LTA	0.53
	Adequate	0.47

For nodes with one, two, or three parents, the conditional probabilities are assessed using marginal probability of the child and each parent, and the equations provided in Section 5.4.2. The marginal probabilities for all[1] parent and child nodes were calculated using Equation 6.1.

		Org. Culture	
		LTA	Adeq.
Machine	LTA	0.36	0.62
	Adequate	0.64	0.38

		Knowledge	
		LTA	Adeq.
Attitude	LTA	0.47	0.87
	Adequate	0.53	0.13

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[1] The marginal probability of *Machine* LTA used to develop this table was set to 50% because there was not sufficient data to populate the conditional probability table based on the data.

	Org. Culture	LTA		Adeq.	
	Resources	LTA	Adeq.	LTA	Adeq.
Complexity	LTA	0.62	0.50	0.57	0.52
	Adequate	0.38	0.50	0.43	0.48

The *Loads/Perceptions* PSF has five parent nodes. The conditional probability table for *Loads/Perceptions* has 32 columns, but it cannot be calculated using the equation set in Section 5.4.2 because of the number of parents. The conditional probability table can be populated through use of expert judgment or through addition of model nodes to reduce the number of parents. Since the model is based on such limited data, the number of parents could change when additional data is added. We have elected to give *Loads/Perceptions* a uniform distribution equal to its marginal probability distribution until more data becomes available. The marginal probability of LTA *Loads/Perceptions* is 0.41.

Conditional probability tables for the Error Context nodes will have to be assessed using expert judgment until there is more data about the PSFs affecting human success events. The HERA database has the framework to collect this data, but the current success data is not suitable for analysis because the retrospective information sources provide very few details about non-error events. Quantification of the EC nodes is discussed further in Section 6.5.

6.4 Model Validity

The models presented in this chapter are quantified based on the available data. They are intended to demonstrate the proposed methodology and illustrate the type of insights that can be obtained through the process. The models presented in this dissertation should not be used to make definitive statements about the PSF relationships. Rather, the models provide guidance on how to gather additional data to improve the quality of the probability estimates.

The available data do not meet ideal conditions for statistical analysis due to the limited quantity of data and the form of the data. All of the available data sources treat the PSFs as a binary variables, either adequate or LTA. Many commonly used tests of model significance (e.g., χ^2 analysis) assume multivariate normality in the data, and binary data violates this assumption.

It is commonly recommended that there be at least $(10 \times n)$ data points to run factor analysis, where n is the number of variables. For the Mixed Expert/Data Model, this requires over 300 data points, but there are only 158 data points available. For the 9-Bubble model, there may be sufficient data quantity, but the data quality leaves much to be desired. There are large data gaps, especially in *HSI, Environment and Physical & Psychological Abilities.* These PSFs tend to be underrepresented in the data due to the low frequency of occurrence and/or reporting.

For polychoric correlation it is common to perform a G^2 test, which is similar to a χ^2 test [123]. However, it is not possible to perform this test for tetrachoric correlation because there are too few degrees of freedom to permit model testing. It has been suggested that it is not necessary to perform these significance tests if the form of the available data sufficiently justifies the use of tetrachoric correlation [100].

We ran goodness-of-fit tests on the factor models as part of the analysis. While the factor analysis is and the goodness-of-fit tests are subject to the limitations discussed above, there were several indicators of significance for the 4-factor model.

For the factor analysis results, the p value for the Minres 4-factor (i.e., 4 Error Context) model is $|p = 0.015|$, which is significant at the $\alpha = 0.01$ level[2]. The 2-, 3-, and 5- factor models did not produce statistically significant p values. Among the various factor models, the 4-factor model also had the lowest ratio of χ^2 vs. degrees of freedom. According to Hatcher, it is common to seek a model with a relatively small chi-square value rather than a non-significant chi-square value, due to the complexity of factor analysis models. For a model with df degrees of freedom, the model may be acceptable if $(\chi^2/df) \leq 2$ (see [124] for further discussion of the significance of this ratio). This ratio was equal to 2.0 for the 4-factor model; this was the lowest ratio of the models tested.

It is important to emphasize that the purpose of these models is to illustrate

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[2] In factor analysis, the null hypothesis is that the model is an adequate representation of the original correlation matrix. The null hypothesis is accepted if $p > \alpha$,

the type of insights that can be gathered through the model development process and to provide a road map for future model development and data collection. Despite the many limitations of the data, the 4-factor model is significant. However, this is not necessarily the final model. As additional data sources appear, it may be possible to run more significance tests on the data. Bayesian statistical techniques could be used to eliminate the need for significance testing. Additional research directions are discussed in Chapter 7.

6.5 Application in Quantification of Human Error Probabilities

One application of the model is to improve estimates of Human Error Probabilities (HEPs). In this section we will show how the notion of Error Contexts (ECs) introduced in Section 5.2.3 can be used in to quantify HEPs.

One expression that can be used to quantify the probability of a Human Failure Event (HFE) as defined in PRA models (particularly in the PRA Event Tree model) is:

$$p(HFE|S) = \sum_{i} \left[p(HFE|C_i) \times p(C_i|S) \right] \tag{6.2}$$

where S= PRA Scenario (essentially defined as a specific sequence of events after an accident initiator), and C_i= Specific “context” i.

This equation provides a conceptual link between qualitative and quantitative parts of HRA. It is possible to use this equation to relate the new models to the current HRA methods such as SPARH [24].

Under some specific modeling assumptions and abstractions, each C_i can be described via a set of context factors, F_{ij} (context factor j for context i):

$$C_i \equiv \{F_{i1}, F_{i2}, \ldots, F_{in}\} \tag{6.3}$$

Examples of F_{ij} are: a specific crew (out of several possible teams), elapsed time in scenario, a specific PSF, or specific operator action. Using context factors as a way of specifying various contexts, the HEP equation can be written as:

$$p(HFE|S) = \sum_{i=1}^{I} p(HFE|F_{i1}, F_{i2}, \ldots, F_{in}) \times p(F_{i1}, F_{i2}, \ldots, F_{in}|S) \tag{6.4}$$

We note that often $F_{ij} = F_j$ for several i, because some factors (e.g., Procedures) remain constant throughout the course of an entire event.

Recall that the ECs from factor analysis imply higher likelihoods of association with human error compared to other combinations of PSFs. These were marked as EC_1, EC_2, EC_3, and EC_4.[3] The set is shown in the BBN in the lower left corner of Figure 6.4. The tree on the right hand side of the figure explains how ECs can be used to describe various human response outcomes during an accident (A). Given an accident (A), and considering only two of the four ECs for simplicity, the presence

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[3] We remind the reader that additional data and analysis may identify new patterns and/or additional error contexts.

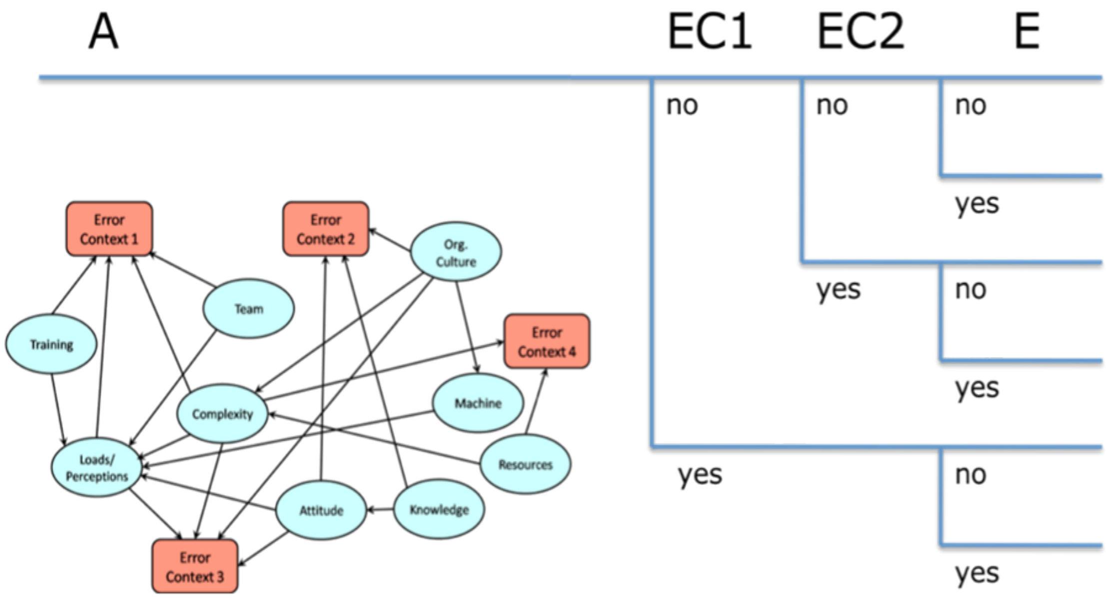

Figure 6.4: Possible effects of Error Contexts on occurrence of HFE given an accident of EC_1 or EC_2 may have an impact on occurrence and likelihood of human error (E).

This picture is a conceptual link between the observed PSF patterns (ECs) and human error probability. This can be accomplished by using Bayes Theorem to “flip” the data:

$$p(E|EC_i, A) = \frac{p(EC_i|E, A) \times p(E|A)}{p(EC_i|E, A) \times p(E|A) + p(EC_i|\overline{E}, A) \times p(\overline{E}|A)} \tag{6.5}$$

Where:

- $P(E|EC_i, A)$ = the probability of error given a specific Error Context EC_i, in accident type A;
- $P(EC_i|E, A)$ = the likelihood of observing Error Context EC_i given an error event E;
- $P(E|A)$ = probability of error E in accident type A.

The above equation enables one to modify a “generic” or “nominal” error probability for a specific error context. This equation would be used in the same way as the SPAR-H equations: an analyst observes the state of several PSFs. However, underlying this equation are the powerful modeling concepts and the understanding of interdependencies that are not captured in current HRA methods.

Quantities $P(EC_i|E, A)$ and $P(EC_i|\overline{E}, A)$ can be obtained through event data collection and analysis, using the PSF hierarchy and the ECs identified according the methodology of this dissertation. The current databases have the capacity to gather this type of data if more detailed sources of information are used. Ideally $P(E|A)$ could also estimated based on data. In the interim however, the nominal reference values used in current HRA methods can be used.

Chapter 7

Conclusions

This dissertation introduced a methodology for building Bayesian Belief Networks of the causal influences among PSFs linked to human error. Three models were produced to illustrate the methodology and its various applications. In addition to the methodology, the dissertation contains a new PSF hierarchy designed specifically for causal modeling. The PSF hierarchy is suitable to be used in both qualitative and quantitative analysis, which will enable multiple HRA methods to use the same PSFs to enable better information sharing.

The PSF hierarchy is intended to be used in next-generation HRA analyses and modeling. The combination of the IDAC structure with the HERA PSFs details has allowed us to produce an orthogonally defined, structured PSF hierarchy. The hierarchy can capture various types of information about natural interdependencies among PSFs, while the orthogonality reduces artificial dependency created by overlapping PSF definitions.

We added specific behaviors and metrics rooted in the data to the PSF set. Some current HRA methods do not differentiate between improper work conduct and the behaviors that demonstrate improper work conduct. These behaviors and metrics are not PSFs, rather they are visible manifestations of unobservable PSFs. Behaviors and metrics must be closely linked to PSFs to increase consistency of interpretation by HRA experts.

During analysis of the data it became apparent that team and organizational factors were at the root of many of the human errors. However, not all human errors were organizationally based. For this reason certain PSFs have been broken down into organizational and personal components. One of the shortcomings of some HRA methods is the blurring of the line between individual and organization. The new set of PSFs contains behavioral elements that parallel each other in the organizational and human sections. Both humans and organizations can display poor work behaviors. In most cases safety culture will influence both sets of work processes, but in the end the human and the organization must each take responsibility for their behaviors. Differentiating between organization and personnel work conduct will allow HRA analysts to better address the source of problems.

Since HRA is a discipline that involves understand the human operator it is very difficult to create and validate a model. Models are largely based on expert opinion and there are no HRA benchmarks that can be used to validate these models. We have created a modeling approach that uses available data to 'validate' the model. Using both expert opinion and available data in the same model provides a level of validity greater than any current HRA model.

7.1 Research Impact

This research is the first application of the data provided in the HERA database. Since the database is still under development at the US NRC, the quantity and quality of data is limited. However, we were able to use the available data to gather insights about PSFs and also about HRA data collection.

The US NRC is currently modifying the HERA structure as part of an SRM project. We have provided feedback to the NRC about the HERA data coding process and the current HERA structure. Some of the insights about the data collection process have already been implemented in the HERA structure and additional insights are addressed by the NRC. Over 50 PSF details have been removed from the original set due to overlap with other PSFs or vague definitions. The NRC is currently working to implement a more orthogonally defined set of PSFs with a hierarchical structure.

7.2 Model Applications

There are several possible applications for causal models of relationships among PSFs that are linked to human error.

1. The model could be integrated into HEP calculations using the methodology outlined in Section 6.5, to provide more informed HEP estimates by considering

interdependencies among PSFs instead of treating them as independent entities.

2. The model can be used to assess the benefits of different risk reduction efforts before they are implemented.
3. The model can be used for informed error management, e.g., to understand and compensate for known weaknesses in the system while long term actions are planned.
4. The model can be used to identify potential variables to manipulate in simulator training or data collection experiments.

The BBN provides a natural framework to assess the benefit of alternative risk reduction strategies or to provide more informed error management. Analysts can use the BBN to record the known state of a PSF and then update the probabilities of the other nodes in the model. Similarly, the analyst can compare different risk mitigation efforts by making observations in the model and seeing how they affect the likelihood of human error. In both situations the analyst can then see which PSFs have the most significant change in probability. Analysts can model different combinations of PSF states to see which system elements have the greatest impact on overall system risk and then identify risk-significant system weaknesses before they result in errors. By evaluating which model nodes have the most significant probability changes, the analyst can better direct their resources at system elements that have the greatest risk impact.

7.3 Future Research Directions

The insights gathered during the data analysis and methodology development offer many possible paths for future research. The PSF hierarchy could be expanded to deeper levels. PSF causal models could be developed for different types of error. Model development is an iterative process, so many of the identified weaknesses of the current models can be addressed in future research. Many of the limitations affecting the entire field of HRA, need to be addressed as part of deeper examination of how the HRA methods relate to each other/could work together.

7.3.1 Data Collection

Many of the data collection problems that limit current HRA will continue to limit advance in HRA until sources of data are improved. The recommendations in this section specifically relate to the HERA database because it is the only human performance database in the nuclear industry, but future databases should also address the following suggestions.

- The HERA structure should be evaluated against the fundamental principles introduced in Section 3. Short term efforts should include:
  - Continuing SRM efforts to redefine PSFs to that they are more orthogonal;
  - Imposing a hierarchical structure on the HERA PSFs to allow data to be aggregated at different levels;

  - Including behaviors and metrics along with the list of PSFs to improve consistent scenario interpretation;
  - Collecting PSF data on a non-binary scale or providing guidance on the threshold between adequate and LTA.

- The HERA database needs to be populated with more data so that more statistical significance can be attached to analysis results.
  - Data collection needs to expand beyond current scope of events. Ideally, it should include errors committed during start up, shutdown, and refueling scenarios.
  - The number of analysts coding HERA events should be increased to produce greater data volume, but also to reduce bias introduced by using a small pool of analysts.

- Need to screen events before coding to evaluate the potential usefulness of the analysis. Some historically significant events (e.g., the fire at Brown's Ferry in the '70s [50] may not be salient for analysis of current plants due to significant changes in the nuclear industry as the result of the event.

- Need HRA databases developed to gather current information

7.3.2 Data Analysis

- Use Bayesian Factor Analysis techniques to develop Error Contexts that contain PSFs with limited information

  - Even if the HERA database is populated with substantial data in the coming years, it is unlikely that all of the PSFs will be accurately represented in the database. We know that reduced fitness for duty contributes to error, but we very rarely see reduced fitness for duty problems reported in any publicly available sources. There are also limited opportunities to report less than adequate environment in the control room
  - Since HERA data will never meet the ideal requirements for factor analysis, it is advisable to perform Bayesian Factor Analysis (BFA). BFA captures uncertainty about factor scores and places fewer constraints on the structure of the input data than traditional FA techniques. BFA provides a natural framework for combining expert and statistical analyses. It allows for the incorporation of different sample sizes and information types through the use of data-informed model weighting parameters [125, 126].

- Address dependency between sub-events within the same event.
  - Cascading Factor Analysis could be applied to recognize the dependency between sub-events by treating sub-events as part of a sequence.

- Address model-fit of the linear factor analysis model to determine how error contexts interrelate.
  - Consider using a non-linear model
  - Consider Latent Class Analysis model

7.3.3 Model Development

- While we believe that the same set of PSFs can be used to describe operator and maintenance personnel performance, the way the PSFs interact may be different. In the future it would be beneficial to see develop models for different types of human error (e.g., error of commission, error of omission), task types (e.g., maintenance, operations), information processing phases (e.g., decision, action), personnel (e.g., operators, management).
- Expand the model to include errors committed by teams/groups (e.g., error in decision made by whole group)
- Consider the effect of worker perception of “observable” PSFs may affect performance. For example, regardless of inherent task complexity, operator perception will vary.

Appendix A

Sample HERA Event

As part of this research the author worked with April Whaley and Pat McCabe, from the Idaho National Laboratory, to learn the HERA coding process and to code several new event analyses into the HERA database. A portion of one of these events is presented in this section. The event is "Fermi 2 – Northeast Blackout LOOP," [51]. The entire Worksheet A is provided, followed by one human failure (XHE) Worksheet B and one human success (HS) Worksheet B. The remainder of the event can be found in the HERA database [2].

Human Event Repository & Analysis (HERA) Worksheet, Part A

Coder: KMG	**2nd Checker**:	**Ops Review**: PHM	**HF Review**:
Date: 18 March 2008	**Date**:	**Date**: **4/14/2008**	**Date**:

Section 1: Plant and Event Overview

Document identifying plant and event information.

1. Primary Source Document: LER 341-2003-002-01
2. Other Source Document(s): IR 341-2003-08; IR 341-2003-009; IR 341-2003-010; ASP 341-2003-002
3. Plant Name: Fermi 2
4. Plant Type: ☒BWR ☐PWR ☐Other: _____
5. Plant Operating Mode: 1

5a. Plant Power Level: 100%

6. Event Type:

☒ Initiating Event ☐ Common Cause

Event Declaration: 0: None

6a. Event Date / Time: August 14, 2003; 16:10. Unusual Event declared at 16:22

6b. Event Description: Loss of electrical load and reactor trip due to Northeast blackout.

7. Affected Function(s): _____
8. Affected System(s): _____
9. Affected Component(s): _____
10. Source:

☒ LER ☒ ASP Analysis ☒ IR ☐ Other _____

CCDP / ΔCDP: 2E-5

☐ Simulator Study

Experiment Information: _____

Scenario: _____

Variant: _____

Crew: _____

11. Similar to other events: ☒Yes ☐No

Comment: See related 08-14-03 Northeast blackout event at Ginna

Section 2: Event Summary / Abstract

Write a brief summary of the event, or copy in the event abstract. Discuss aspects of the event that are important from a HRA perspective. See Coding Manual for guidance.

On August 14, 2003, at approximately 1610 hours, the Reactor Protection System initiated an automatic reactor scram from 100% power as a result of a Turbine Control Valve (TCV) fast closure. The TCV closure was caused by a turbine trip signal initiated by the main turbine-generator protective control system upon sensing electrical grid voltage fluctuations. A Loss of Offsite Power occurred as a result of the regional electric grid disturbance that affected several eastern and central states and portions of Canada and that led to blackout conditions in a large portion of the United States.

All safety related systems operated as expected in response to this event. All control rods fully inserted into the reactor core. Reactor Pressure Vessel (RPV) water level decreased and the Reactor Core Isolation Cooling system was manually started to restore RPV level; however, the High Pressure Coolant Injection system automatically started when RPV water level reached the setpoint for Level 2. Primary containment penetration isolations associated with RPV Level 3 and 2 setpoints occurred as expected . All Main Steam Isolation Valves closed and all four Emergency Diesel Generators started and energized their pertinent emergency loads. Nine Safety Relief Valves lifted and reseated. Combustion Turbine Generator (CTG) 11-1 did not initially start in response to this event.

Human performance issues were identified as the root cause of the failure of CTG 11-1 to start. Maintenance personnel made an error when installing CTG 11-1 because they did not follow the proper modification process. Error was repeated during subsequent replacement as well. Additional work independent of this error performed on CTG 11-1 also contributed to the failure. This error was due to inadequate procedural guidance for specific maintenance tasks.

Section 3: Key Human Performance Insights

Outline key deviations from nominal performance, important observations about human performance, and causes.

Latent faults:
CTG 11-1 inverter set point was not adjusted when part was installed.
Effect: CECO was not updated

CTG 11-1 CECO not updated.
Effect: Error was repeated.

CTG 11-1 set point error repeated
Effect: CTG 11-1 failed to start on demand during Unusual Event.

CTG 11-1 fuel oil pump arcing horn problems due to lack of procedures.
Effect: CTG 11-1 failed to start on demand during Unusual Event

Key human faults:
The set point error was repeated twice:
The CTG 11-1 inverter set point was not adjusted when the part was installed; a maintenance personnel mistake. This mistake was corrected 6 months later, but there is no information that implies that the personnel alerted others to this problem. When the card was replaced several years later, the original set point mistake was repeated. There is no available information that discusses if the first mistake was discovered or corrected by chance.

Factors contributing to inadequate maintenance could be related to licensee scheduling of preventative maintenance: Specifically, the licensee's process of including a 25 percent grace period on most preventive maintenance tasks could allow a component to remain in service longer than the design basis lifetime, thus reducing the reliability of that component. Implementation of a grace period could be a sign of greater organizational or staffing/workload problems.

There is no indication that the errors related to the CTG 11-1 inverter set points are at all related to the CTG 11-1 fuel oil pump error.

Corrective actions taken:
Updated procedures for CTG 11-1 fuel oil pump maintenance to include arcding horn required clearance and instructions to check arcing horn

Updated CTG 11-1 set point information in CECO.

Section 4: Index of Subevents

Provide a brief description of all subevents as well as subevent codes (XHE, HS, EE, XEQ, EQA, PS, or CI), date and time, work type and personnel involved (for all human subevents; see manual for codes), whether the subevent was pre-initiator (PRE), initiator (INIT), or post-initiator (POST), whether the subevent was active (A) or latent (L),and, if the subevent is an XHE, if it was an error of omission (O) or commission (C) or indeterminate (I). Indicate the Human Action Category number for XHEs and HSs (see manual), indicate whether a HS is a recovery, indicate whether the XHE or HS receives Worksheet B coding, list any related subevents, both prior and following the subevent, any comments (e.g., why a subevent is not receiving Worksheet B coding, contributing performance shaping factors), and whether the subevent will be included on the graphical timeline. See the coding manual for guidance on subevent breakdown and subevent code assignment. Use additional sheets as necessary.

Subevent Code	Date / Time	Work Type	Personnel	Pre / Initiator / Post	Latent / Active	Omission / Commission	Description	Human Action Category	Recovery	Worksheet B	Related Subevents	Comments	Graph
XEQ1	2/15/1996		M-S	PRE			CTG 11-1 classified as inoperable due to a large number of failures and poor reliability; failure to meet maintenance rule criteria. A multimillion dollar project for major upgrades began.		☐	☐			☐
CI1	1996	F	M-S	PRE			Originally, a motor generator (MG) set on station blackout combustion turbine generator (CTG) 11-1 was used to provide 120VAC control power and power to the exciter. A decision was made in 1996 to replace the MG set with an inverter. No documentation justifying the reason for the change existed.		☐	☐			☐
XHE 1	1996	M	M-M M-I	PRE	L	O	The inverter came from the vendor with factory set low and high inverter voltage trip set points based on a system that has a battery bank of 60 cells. The low voltage set point is determined at 1.75 volts/cell thereby establishing a 105-volt low factory set point. However, CTG 11-1 has a 56-cell battery bank, which required that the low voltage factory set point be changed to 98 volts. The inverter was installed without changing the set points. Installing the circuit card without properly adjusting the set point was the result of inadequate implementation of the modification process.	5	☐	☒	XEQ1, CI1, HS2	See section 6. Worksheet B cluster includes XHE1 and XHE2.	☐
XHE2	1996	A	M-I	PRE	L	O	Because the modification process was not used, the central component (CECO) information database that contains design basis information, particularly set point values, was not updated to reflect the correct set points.	13	☐	☐	XHE1, CI1	Worktype - A and M See section 6. Worksheet B cluster includes XHE1 and XHE2.	☐
XEQ2	1997			PRE			CTG 11-1 returned to service after upgrades. Then, CTG 11-1 removed from service for 5 additional months for substantial maintenance.		☐	☐	XEQ1		☐

Subevent Code	Date / Time	Work Type	Personnel	Pre / Initiator / Post	Latent / Active	Omission / Commission	Description	Human Action Category	Recovery	Worksheet B	Related Subevents	Comments	Graph
HS1	~1997	M	M-M M-I	PRE			The inverter had the incorrect low voltage set points for about 6 months until the set point card S2A-167 was changed. During this card replacement, personnel referenced the vendor manual and recognized the 1.75 volt/cell requirement, counted 56 cells on CTG 11-1 and correctly adjusted the low voltage trip set point to 98 volts, installed the card and placed CTG 11-1 in service.	5	☒	☒		Partial recovery of XHE1	☐
PS1	10/15/1999			PRE			CTG 11-1 returned to service.		☐	☐			☐
PS2	DECEMBER 2000			PRE			CTG 11-1 maintenance rule performance criteria exceeded "less than 3 failures in the last 20 demands." 14 functional failures of CTG 11-1 recorded between 12/6/2000 and 8/14/2003.		☐	☐			☐
XEQ3	1/9/2001			PRE			CTG classified as failed due to maintenance rule.		☐	☐	PS2		☐
XEQ4	1/9/2001			PRE			The CTG 11-1 inverter set point card burned out.		☐	☐	PS2, XEQ3		☐
XHE3	8/22/2001	M	M-M M-I S-P	PRE	L	O	The CTG 11-1 inverter set point card was replaced. Since CECO did not contain the correct low voltage trip set points, the work package to replace the card did not include instructions to change the factory set low voltage trip set point of 105 volts to 98 volts. The replacement set point card and inverter were set to a low voltage trip set point of 105 volts, which was too high for the CTG 11-1 inverter set point requirement of 98 volts.	5	☐	☒	XHE1, XHE2, CI1	Worktype - M and P See section 6.	☐
XHE4	5/30/2003 – 8/14/2003	M	M-E S-P	PRE	L	O	Preventive maintenance on the CTG 11-1 DC fuel oil pump was inadequate in that the verification and /or adjustment of the arcing horn critical clearance dimensions was not specified or required. There was no requirement to check the arcing horn clearances during preventive maintenance.	5	☐	☒		Worktype M and P	☐
XEQ5	BETWEEN 5/30/2003 AND 8/14/2003			PRE			The CTG 11-1 DC fuel oil pump starter contactor began to stick open against its arcing horn. The contactor was hanging up on the lower portion of an arcing horn (used for arc suppression drain) which prevented the contact from fully closing. The contactor worked properly when last tested on May 30, 2003 and during all previous tests, but became inoperable at some point between May 30, 2003 and August 14, 2003.		☐	☐	XHE4		☐

Subevent Code	Date / Time	Work Type	Personnel	Pre / Initiator / Post	Latent / Active	Omission / Commission	Description	Human Action Category	Recovery	Worksheet B	Related Subevents	Comments	Graph
EE 1	8/14/2003; 1605			PRE			On the afternoon of August 14, 2003, a regional electric grid disturbance occurred in several eastern and central states and portions of Canada that led to blackout conditions in a large portion of the United States. At approximately 1605 hours, plant operators noted voltage fluctuations on the grid.		☐	☐			☐
EQA1	8/14/2003; 1610			PRE			Continuing grid instability resulted in a turbine trip initiated by the main turbine-generator protective control system.		☐	☐	EE1		☐
EQA2	8/14/2003; 1610			INIT			A Turbine Control Valve (TCV) fast closure occurred and the Reactor Protection System (RPS) initiated a reactor scram as a result of the turbine trip. All control rods fully inserted into the reactor core		☐	☐			☐
CI2	8/14/2003		N-R	POST			From the control room, the inspectors monitored plant conditions and operator actions to ensure that the plant was responding as designed, that all relevant procedures were being followed. The inspectors walked down the control panels, reviewed various procedures, drawings, Technical Specifications, and other licensee documentation, and interviewed various plant personnel. The inspectors reviewed the Transient Analysis Program report and compared plant response to the expected response as detailed in the UFSAR.		☐	☐			☐
EE2	8/14/2003; 1611			POST			At approximately 1611 hours, offsite power was lost.		☐	☐	EE1		☐
EQA3	8/14/2003; 1611			POST			All Main Steam Isolation Valves (MSIVs) closed due to the loss of RPS power caused by the Loss of Offsite Power (LOSP)		☐	☐	EE2		☐
EQA4	8/14/2003; 1611			POST			Three EDGs (11, 12 and 14) automatically started from standby and loaded as expected.		☐	☐			☐
HS2	8/14/2003; 1611	O	O-C O-A	POST			EDG 13 was out of service undergoing a monthly surveillance run (this entailed being loaded to the grid); however, the EDG went off-line at the loss of offsite power and operators transferred it from the test mode and lined up to its emergency mode of operation within one minute of the other EDGs.	9	☐	☐			☐
PS3	8/14/2003; 1612			POST			LOSP caused the loss of Feedwater flow and a decrease in Reactor Pressure Vessel (RPV) water level.		☐	☐	EQA3		

Subevent Code	Date / Time	Work Type	Personnel	Pre / Initiator / Post	Latent / Active	Omission / Commission	Description	Human Action Category	Recovery	Worksheet B	Related Subevents	Comments	Graph
HS3	8/14/2003; 1613	O	O-C	POST			The Reactor Core Isolation Cooling (RCIC) system was manually started to restore RPV level.	9	☐	☐			
EQA5	8/14/2003; 1615			POST			High Pressure Coolant Injection (HPCI) system automatically started when RPV water level reached the set point for Level 2.		☐	☐	HS3		
EQA6	8/14/2003; 1615			POST			HPCI and RCIC were used to supply water to the RPV until they both tripped on Level 8.		☐	☐	EQA5		
HS4	8/14/2003; 1618	O	O-C	POST			RCIC was then manually restarted and used for level control. The operators noted a minimum RPV level of 112 inches above the Top of Active Fuel. Primary containment penetration isolations associated with RPV Level 3 and 2 setpoints occurred as expected	9	☐	☐			
EQA7	8/14/2003; 1621			POST			Following MSIV closure, nine Safety Relief Valves (SRVs) lifted and reseated. Peak RPV pressure was about 1140 psig.		☐	☐	EQA3		
CI3	8/14/2003; 1625	O	O-C	POST			Reactor pressure was then automatically controlled using the Low-Low Set mode of SRV A throughout the remainder of the event and recovery until the MSIVs were reopened and the main condenser was restored as a heat sink.		☐	☐	EQA7		

Subevent Code	Date / Time	Work Type	Personnel	Pre / Initiator / Post	Latent / Active	Omission / Commission	Description	Human Action Category	Recovery	Worksheet B	Related Subevents	Comments	Graph
XEQ6	8/14/2003; 1625			POST			The operators attempted to start Combustion Turbine Generator [TG] (CTG) 11-1, to power the balance of plant (BOP) buses; however, the CTG failed to start due to the trip of a battery-powered inverter which provides power to the igniters used to start the CTG; An initial attempt to start CTG 11-1 using DC power from the batteries failed because the large voltage drop during the start sequence had dropped below 105 volts and the inverter tripped. The starting diesel was running and the CTG turbine shaft was spinning but the CTG was not firing. Combustion Turbine Generator 11-1 was not firing because the inverter, which is used for powering the two igniters on the CTG, had lost power. Several attempts to restart the inverter were unsuccessful. After the event, inspectors determined that CTG 11-1 failed to start during the loss of offsite power event because the inverter low voltage trip set point was set too high (see XHE 3).		☐	☐	XHE1, XHE2, XHE3, XHE4, XEQ1, XEQ3, XEQ4, XEQ5		
CI4	8/14/2003; 1622	O	O-S S-D	POST			Unusual Event declared.		☐	☐		Worktype O and B	
XEQ7	8/14/2003; 1655-1700			POST			With a shift manager's authorization, two additional attempts were made to start CTG 11-1 using a portable 120VAC generator connected to the inverter, but the CTG tripped at partial speed due to a "loss of flame" and a "failure to ignite" signal. These signals were generated because the contactor for an emergency fuel forwarding pump had failed (see XEQ 1).		☐	☐	XE5, XHE4		
HS5	8/14/2003; 1730	O	O-C O-A	POST			The sticking CTG 11-1 fuel oil pump contactor was detected and accounted for within about 35 minutes of the CTG 11-1 start delay.	6	☐	☒	XEQ5, XHE4	Partial recovery of XHE6	
HS 6	8/14/2003; 1919	B	O-A M-S M-E	POST			The CTG was locally started later that afternoon, around 1919 hours. While holding the fuel oil pump contactor together by hand, the emergency fuel forwarding pump was started and a third attempt at starting CTG 11-1 was successful using an alternate source of starting power provided by a portable 120VAC generator.	10	☒	☒	XEQ1, XEQ2, XEQ3, XEQ4, XEQ5	Worktype B, O, M. Recovery from XEQ6	

Subevent Code	Date / Time	Work Type	Personnel	Pre / Initiator / Post	Latent / Active	Omission / Commission	Description	Human Action Category	Recovery	Worksheet B	Related Subevents	Comments	Graph
HS 7	8/14/2003; 1919+	O	O-C	POST			Restoration of electrical power continued in accordance with procedures.	13	☐	☐			
EE3	8/14/2003; 2230			POST			Offsite power was restored to the switchyard.		☐	☐			
HS8	8/15/2003; 0153	O	O-C	POST			First emergency bus (10600) was switched to offsite power source and EDG 14 was shut down.	1	☐	☐			
HS9	8/15/2003; 0412	O	O-C	POST			0412 Second emergency bus (10500) was switched to offsite power source and EDG 13 was shut down.	1	☐	☐	HS8		
HS10	8/15/2003; 1332	O	O-C	POST			Offsite power was fully restored to the plant and all emergency diesel generators were shut down.	1	☐	☐			
CI5	8/15/2003; 1348	O	O-S S-D	POST			Unusual Event was terminated.		☐	☐		?	

Section 5: General Trends Across Subevents / Lessons Learned

Part A: General Trends ☒ **Not Applicable**

Indicate any strong, overarching trends or context across the subevents and provide a detailed explanation. This section is optional and only used when an issue is seen repeatedly throughout the event, to highlight the trend that may not be readily evident from the separate Worksheet B coding.

Trend	Comment
☐ Procedures (e.g., repeated failure to use or follow procedures)	
☐ Workarounds (e.g., cultural acceptance of workarounds contributes to multiple subevents)	
☐ Strong mismatch (e.g., between operator expectations compared to evolving plant conditions; between communications goals compared to practice; between complexity and speed of event compared to training and procedural support; between operator mental model and actual event progression)	
☐ Deviation from previously analyzed or trained scenarios	
☐ Extreme or unusual conditions	
☐ Strong pre-existing conditions	
☐ Misleading or wrong information, such as plant indicators or procedures	
☐ Information rejected or ignored	
☐ Multiple hardware failures	
☐ Work transitions in progress	
☐ Focus on production over safety	
☐ Configuration management failures including drawings and tech specs, such as incorrect room penetrations, piping or equipment configurations	
☐ Failure in communication or resource allocation	
☐ Other: _____	

Part B: Lessons Learned ☒ **Not Applicable**

Explain any key lessons learned from this event and / or any key corrective actions taken as a result of this event.

_____

Section 6: Human Subevent Dependency Table

Place only the XHEs that receive Worksheet B coding on the top row and in the left column of the pyramid table. Check the appropriate boxes to indicate dependency between subevents. See the coding manual for guidance on assigning dependency. Provide explanation in the Comment table below to explain the factors that caused the subevents to exhibit dependency. Common dependency factors are listed in the pyramid table. Use additional sheets as necessary.

Subevent Code	XHE 1	XHE2	XHE3	XHE4											
XHE1		☒	☒	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
XHE2			☒	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
XHE3				☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
XHE4					☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
						☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
							☐	☐	☐	☐	☐	☐	☐	☐	☐
								☐	☐	☐	☐	☐	☐	☐	☐
									☐	☐	☐	☐	☐	☐	☐
										☐	☐	☐	☐	☐	☐
											☐	☐	☐	☐	☐
												☐	☐	☐	☐
													☐	☐	☐
														☐	☐
															☐

Common Dependency Factors:

- Similar Task
- Same person/people
- Close in time
- Same location/same equipment
- No independent oversight
- Same cues
- Action prompts next incorrect action
- Similar environmental conditions
- Unreliable system feedback
- Prior human failures on same equipment
- Lack of intervening human success
- Cultural dependency
- Mindset
- Work Practices
- Other (explain)

Row Subevent	**Column Subevent**	**Affects >1 subsequent subevent**	**Comment**
XHE1	XHE2	☐	Failure to follow modification procedure in XHE1 implies that maintenance personnel were unaware of the need to change the set points, and without knowing that these need to be changed there would be no need to update the CECO information in XHE2.
XHE2	XHE3	☐	Since CECO information was not updated in XHE2, maintenance personnel did not know to update the set point in XHE3.
		☐	
		☐	
		☐	
		☐	
		☐	
		☐	
		☐	
		☐	

Human Event Repository & Analysis (HERA) Worksheet, Part B

Source Document: LER50-341-2003-002 Subevent Code: XHE1

Description:
Includes XHE1 and XHE2
The inverter came from the vendor with factory set low and high inverter voltage trip set points based on a system that has a battery bank of 60 cells. The low voltage set point is determined at 1.75 volts/cell thereby establishing a 105-volt low factory set point. However, CTG 11-1 has a 56-cell battery bank, which required that the low voltage factory set point be changed to 98 volts. The inverter was installed without changing the set points. Installing the circuit card without properly adjusting the set point was the result of inadequate implementation of the modification process.

Because the modification process was not used, the central component (CECO) information database that contains design basis information, particularly set point values, was not updated to reflect the correct set points

Section 1: Personnel Involved in Subevent

Indicate which personnel were involved in the subevent. Check all that apply.

- ☐ Operations (OPS)
  - ☐ OPS Supervisors
  - ☐ Control Room (CR) Operators
  - ☐ Outside of CR Operators
  - ☐ Technical Support Center (TSC)
- ☐ Maintenance and Testing
  - ☐ Maintenance Supervision / Planning
  - ☒ Mechanical
  - ☐ Electrical
  - ☒ I&C
- ☐ Management
- ☐ Plant Support Personnel
  - ☐ Administrative Support
  - ☐ Chemistry
  - ☐ Emergency Planning / Response
  - ☐ Engineering
  - ☐ Fitness for Duty
  - ☐ Fuel Handling
  - ☐ Health Physics
  - ☐ Procedure Writers
  - ☐ QA / Oversight
  - ☐ Security
  - ☐ Training
  - ☐ Shipping / Transportation
  - ☐ Specialized Task Force
  - ☐ Work Control
  - ☐ Licensing / Regulatory Affairs
- ☐ Site-Wide
- ☐ Non-Plant Personnel
  - ☐ Contractor Personnel
  - ☐ Manufacturer
  - ☐ NRC / Regulator
  - ☐ Vendor
- ☐ Other: _____

Section 2: Plant Conditions

Part A: Contributing Plant Conditions

Indicate plant conditions that contribute to this subevent, and / or influence the decisions and / or actions of personnel. Leave a detailed comment, with reference to the source document.

Plant Condition	Comment
☐ Equipment installed does not meet all codes / requirements	
☐ Manufacturer fabrication / construction inadequate	
☐ Specifications provided by manufacturer inadequate	
☐ Documents, drawings, information, etc., provided by the manufacturer incorrect or inadequate	
☐ Substitute parts / material used do not meet specifications	
☐ Material used inadequate	
☐ QA requirements not used or met during procurement process	
☐ Post-procurement requirements not used / performed	
☐ Lack of proper tools / materials	
☒ Installation workmanship inadequate	
☐ Equipment failure / malfunction	
☐ System / train / equipment unavailable	
☐ Instrumentation problems / inaccuracies	
☐ Control problems	
☐ Plant / equipment not in a normal state	
☐ Plant transitioning between power modes	

Plant Condition	Comment
☐ Loss of electrical power	
☐ Reactor scram / plant transient	
☐ Fire	
☐ Other: _____	
☐ None / Not Applicable / Indeterminate	

Part B: Effects on Plant ☐ Check to Exclude

Indicate the effects of this subevent on the plant.

1. Affected Function(s): Human Performance [D] - Work Practices
2. Affected System(s): ACP
3. Affected Component(s): ACP: INV

Section 3: Positive Contributory Factors / PSF Details

Indicate any positive factors beyond what is nominally expected that contributed to the subevent. Check all that apply; if no details apply for a PSF category, check None. Indicate whether the detail is selected based on evidence directly from the source or if it is coder inference. Leave a detailed comment, with reference to the source document. This information is used to calculate the Performance Shaping Factor (PSF) level in Section 5. This table continues on the next page.

PSF	Positive Contributory Factor	Source / Inference	Comment
Available Time	☐ More than sufficient time given the context	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Stress & Stressors	☐ Enhanced alertness / no negative effects	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Complexity	☐ Failures have single vs. multiple effects	☐ Source ☐ Inferred	
	☐ Causal connections apparent	☐ Source ☐ Inferred	
	☐ Dependencies well defined	☐ Source ☐ Inferred	
	☐ Few or no concurrent tasks	☐ Source ☐ Inferred	
	☐ Action straightforward with little to memorize and with no burden	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Experience & Training	☐ Frequently performed / well-practiced task	☐ Source ☐ Inferred	
	☐ Well qualified / trained for task	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Procedures & Reference Documents	☐ Guidance particularly relevant and correctly directed the correct action or response	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Ergonomics & HMI	☐ Unique features of HMI were particularly useful to this situation	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Fitness for Duty / Fatigue	☐ Optimal health / fitness was key to the success	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Work Processes	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Planning / Scheduling	☐ Correct work package development important to the success	☐ Source ☐ Inferred	
	☐ Work planning / staff scheduling important to the success	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Supervision / Management	☐ Clear performance standards	☐ Source ☐ Inferred	
	☐ Supervision properly involved in task	☐ Source ☐ Inferred	

PSF	Positive Contributory Factor	Source / Inference	Comment
	☐ Supervision alerted operators to key issue that they had missed	☐ Source ☐ Inferred	
	☐ Pre-task briefing focused on failure scenario that actually occurred / discussed response plans that were directly applicable	☐ Source ☐ Inferred	
	☐ Pre-task briefing alerted operators to potential problems in a way that made them alert to the situation that developed	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Conduct of Work	☐ Quick identification of key information was important to success	☐ Source ☐ Inferred	
	☐ Error found by 2nd checker, 2nd crew, or 2nd unit	☐ Source ☐ Inferred	
	☐ Important information easily differentiated	☐ Source ☐ Inferred	
	☐ Determining appropriate procedure to use in unique situation was important to success	☐ Source ☐ Inferred	
	☐ Complex system interactions identified and resolved	☐ Source ☐ Inferred	
	☐ Remembered omitted step	☐ Source ☐ Inferred	
	☐ Difficult or potentially confusing situation well understood	☐ Source ☐ Inferred	
	☐ Safety implications identified and understood in a way that was important to success	☐ Source ☐ Inferred	
	☐ Acceptance criteria understood and properly applied to resolve difficult situation	☐ Source ☐ Inferred	
	☐ Proper post-modification testing identified and ensured resolution of significant problem	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Problem Identification & Resolution (PIR) / Corrective Action Plan (CAP)	☐ Good trending of problems was important in correct diagnosis / response plan revision	☐ Source ☐ Inferred	
	☐ Adaptation of industry notices / practices was key to correct diagnosis / response plan verification	☐ Source ☐ Inferred	
	☐ Good corrective action plan avoided serious problems	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Communication	☐ Communications practice was key to avoiding severe difficulties	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Environment	☐ Environment particularly important to success	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Team Dynamics / Characteristics	☐ Extraordinary teamwork and / or sharing of work assignments was important to success	☐ Source ☐ Inferred	
	☐ Exceptional coordination / communications clarified problems during event	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.

Section 4: Negative Contributory Factors / PSF Details

Indicate any negative factors that contributed to the subevent. Check all that apply; if no details apply for a PSF category, check None. Indicate whether the detail is selected based on evidence directly from the source or if it is coder inference. Leave a detailed comment, with reference to the source document. This information is used to calculate the Performance Shaping Factor (PSF) level in Section 5. This table continues over the next three pages.

PSF	Negative Contributory Factor	Source / Inference	Comment
Available Time	☐ Limited time to focus on tasks	☐ Source ☐ Inferred	
	☐ Time pressure to complete task	☐ Source ☐ Inferred	
	☐ Inappropriate balance between available and required time	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	

PSF	Negative Contributory Factor	Source / Inference	Comment
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Stress & Stressors	☐ High stress	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Complexity	☐ High number of alarms	☐ Source ☐ Inferred	
	☐ Ambiguous or misleading information present	☐ Source ☐ Inferred	
	☐ Information fails to point directly to the problem	☐ Source ☐ Inferred	
	☐ Difficulties in obtaining feedback	☐ Source ☐ Inferred	
	☐ General ambiguity of the event	☐ Source ☐ Inferred	
	☐ Extensive knowledge regarding the physical layout of the plant is required	☐ Source ☐ Inferred	
	☐ Coordination required between multiple people in multiple locations	☐ Source ☐ Inferred	
	☐ Scenario demands that the operator combine information from different parts of the process and information systems	☐ Source ☐ Inferred	
	☐ Worker distracted / interrupted (W2 198)	☐ Source ☐ Inferred	
	☐ Demands to track and memorize information	☐ Source ☐ Inferred	
	☐ Problems in differentiating important from less important information	☐ Source ☐ Inferred	
	☐ Simultaneous tasks with high attention demands	☐ Source ☐ Inferred	
	☐ Components failing have multiple versus single effects	☐ Source ☐ Inferred	
	☐ Weak causal connections exist	☐ Source ☐ Inferred	
	☐ Loss of plant functionality complicates recovery path	☐ Source ☐ Inferred	
	☐ System dependencies are not well defined	☐ Source ☐ Inferred	
	☐ Presence of multiple faults	☐ Source ☐ Inferred	
	☐ Simultaneous maintenance tasks required or planned	☐ Source ☐ Inferred	
	☐ Causes equipment to perform differently during the event	☐ Source ☐ Inferred	
	☐ Subevent contributes to confusion in understanding the event	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Experience & Training	☐ Fitness for Duty (FFD) training missing / less than adequate (LTA) (F 124)	☐ Source ☐ Inferred	
	☐ Training LTA (T 100)	☐ Source ☐ Inferred	
	☐ Training process problem (T 101)	☐ Source ☐ Inferred	
	☐ Individual knowledge problem (T 102)	☐ Source ☐ Inferred	
	☐ Simulator training LTA (T4 103)	☐ Source ☐ Inferred	
	☐ Work practice or craft skill LTA (W2 188)	☐ Source ☐ Inferred	
	☐ Not familiar with job performance standards	☐ Source ☐ Inferred	
	☐ Not familiar / well practiced with task	☐ Source ☐ Inferred	
	☐ Not familiar with tools	☐ Source ☐ Inferred	
	☐ Not qualified for assigned task	☐ Source ☐ Inferred	
	☐ Training incorrect	☐ Source ☐ Inferred	
	☐ Situation outside the scope of training	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Procedures & Reference Documents	☐ No procedure / reference documents (P 110)	☐ Source ☐ Inferred	
	☐ Procedure / reference document technical content less than adequate (LTA) (P 111)	☐ Source ☐ Inferred	
	☐ Procedure / reference document contains human factors deficiencies (P 112)	☐ Source ☐ Inferred	
	☐ Procedure / reference document development and maintenance LTA (P 113)	☐ Source ☐ Inferred	
	☐ Procedures do not cover situation	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Ergonomics & HMI	☐ Alarms / annunciators less than adequate (LTA) (H1)	☐ Source ☐ Inferred	
	☐ Controls / input devices LTA (H2)	☐ Source ☐ Inferred	
	☐ Displays LTA (H3)	☐ Source ☐ Inferred	
	☐ Panel or workstation layout LTA (H4)	☐ Source ☐ Inferred	
	☐ Equipment LTA (H5)	☐ Source ☐ Inferred	

PSF	Negative Contributory Factor	Source / Inference	Comment
	☐ Tools and materials LTA (H6)	☐ Source ☐ Inferred	
	☐ Labels LTA (H7)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Fitness for Duty / Fatigue	☐ Working continuously for considerable number of hours	☐ Source ☐ Inferred	
	☐ Working without rest day for considerable time	☐ Source ☐ Inferred	
	☐ Unfamiliar work cycle	☐ Source ☐ Inferred	
	☐ Frequent changes of shift	☐ Source ☐ Inferred	
	☐ Problem related to night work	☐ Source ☐ Inferred	
	☐ Circadian factors / individual differences (F 127)	☐ Source ☐ Inferred	
	☐ Impairment (F 129)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Work Processes	☐ Other: _____	☐ Source ☐ Inferred	
	☐ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	
Planning / Scheduling	☐ Work planning does not control excessive continuous working hours (F 125)	☐ Source ☐ Inferred	
	☐ Inadequate staffing / task allocation (W1 181)	☐ Source ☐ Inferred	
	☒ Scheduling and planning less than adequate (LTA) (W1 180)	☒ Source ☐ Inferred	Fermi has a policy that allows preventative maintenance to be performed up to 25% later than recommended time. Scheduling of preventative maintenance was inadequate.
	☐ Work package quality LTA (W1 182)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☐ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	.
Supervision / Management	☐ Administrative assurance of personnel ability and qualification to perform work less than adequate (LTA) (F 120-122)	☐ Source ☐ Inferred	
	☒ Inadequate supervision / command and control (O1 130)	☒ Source ☐ Inferred	Supervisors were not aware of failure to follow modification process, or supervisors did nothing to correct this.
	☐ Management expectations or directions less than adequate (O1 131)	☐ Source ☐ Inferred	
	☐ Duties and tasks not clearly explained / work orders not clearly given	☐ Source ☐ Inferred	
	☐ Progress not adequately monitored	☐ Source ☐ Inferred	
	☐ Inadequate control of contractors	☐ Source ☐ Inferred	
	☐ Frequent task re-assignment	☐ Source ☐ Inferred	
	☐ Pre-job activities (e.g., pre-job briefing) LTA (W1 183)	☐ Source ☐ Inferred	
	☒ Safety aspects of task not emphasized	☒ Source ☐ Inferred	Management routinely exceeded the recommended time between preventative maintenance tasks.
	☐ Informally sanctioned by management	☐ Source ☐ Inferred	
	☒ Formally sanctioned workarounds cause problem	☒ Source ☐ Inferred	Licensee routinely allowed the 25% grace period.
	☐ Other: _____	☐ Source ☐ Inferred	
	☐ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	
Conduct of Work	☐ Self-check less than adequate (LTA) (W2 197)	☐ Source ☐ Inferred	
	☐ Improper tools or materials selected / provided / used	☐ Source ☐ Inferred	
	☐ Necessary tools / materials not provided or used	☐ Source ☐ Inferred	
	☒ Information present but not adequately used	☒ Source ☐ Inferred	Personnel had access to vendor manual specifying set point volt per cell requirements.
	☐ Failure to adequately coordinate multiple tasks / task partitioning / interruptions	☐ Source ☐ Inferred	
	☐ Fitness for Duty self-declaration LTA (F 123)	☐ Source ☐ Inferred	
	☐ Fitness for Duty non-compliance (F 128)	☐ Source ☐ Inferred	
	☐ Control room sign off on maintenance not performed	☐ Source ☐ Inferred	
	☐ Tag outs LTA (W1 184)	☐ Source ☐ Inferred	
	☐ Second independent checker not used or available	☐ Source ☐ Inferred	
	☐ Work untimely (e.g., too long, late) (W2 192)	☐ Source ☐ Inferred	
	☐ Housekeeping LTA (W2 194)	☐ Source ☐ Inferred	
	☐ Logkeeping or log review LTA (W2 195)	☐ Source ☐ Inferred	

PSF	Negative Contributory Factor	Source / Inference	Comment
	☐ Independent verification / plant tours LTA (W2 196)	☐ Source ☐ Inferred	
	☒ Procedural adherence LTA (W2 185)	☒ Source ☐ Inferred	Maintenance personnel did not follow established modification process.
	☐ Failure to take action / meet requirements (W2 186)	☐ Source ☐ Inferred	
	☐ Action implementation LTA (W2 187)	☐ Source ☐ Inferred	
	☐ Recognition of adverse condition / questioning LTA (W2 189)	☐ Source ☐ Inferred	
	☐ Failure to stop work / non conservative decision making (W2 190)	☐ Source ☐ Inferred	
	☐ Non-conservative action (W2 193)	☐ Source ☐ Inferred	
	☐ Failure to apply knowledge	☐ Source ☐ Inferred	
	☐ Failure to access available sources of information	☐ Source ☐ Inferred	
	☐ Post-modification testing inadequate	☐ Source ☐ Inferred	
	☐ Post-maintenance testing inadequate	☐ Source ☐ Inferred	
	☐ Retest requirements not specified	☐ Source ☐ Inferred	
	☐ Retest delayed	☐ Source ☐ Inferred	
	☐ Test acceptance criteria inadequate	☐ Source ☐ Inferred	
	☐ Test results review inadequate	☐ Source ☐ Inferred	
	☐ Surveillance schedule not followed	☐ Source ☐ Inferred	
	☐ Situational surveillance not performed	☐ Source ☐ Inferred	
	☐ Required surveillance / test not scheduled	☐ Source ☐ Inferred	
	☐ Incorrect parts / consumables installed / used	☐ Source ☐ Inferred	
	☐ Failure to exclude foreign material	☐ Source ☐ Inferred	
	☐ Incorrect restoration of plant following maintenance / isolation / testing	☐ Source ☐ Inferred	
	☐ Independent decision to perform work around or circumvention	☐ Source ☐ Inferred	
	☐ Other: ______	☐ Source ☐ Inferred	
	☐ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	
Problem Identification & Resolution (PIR) / Corrective Action Plan (CAP)	☐ Problem not completely or accurately identified (R1 140)	☐ Source ☐ Inferred	
	☒ Problem not properly classified or prioritized (R1 141)	☒ Source ☐ Inferred	Management was aware of continuing problems with CTG 11-1. CTG 11-1 had been overhauled in 1996, underwent major maintenance in 1997; After 1999 CTG 11-1 failed maintenance performance criteria of less than 3 failures in 20 demands. 14 failures related to CTG 11-1 were observed between December 2000 and the time of this event.
	☐ Operating experience review less than adequate (LTA) (R1 142)	☐ Source ☐ Inferred	
	☐ Failures to respond to industry notices or follow industry practices	☐ Source ☐ Inferred	
	☒ Tracking / trending LTA (R1 143)	☒ Source ☐ Inferred	Management was aware of continuing problems with CTG 11-1 but did not establish interim corrective actions to ensure that unit started on demand.
	☐ Root cause development LTA (R2 145)	☐ Source ☐ Inferred	
	☐ Evaluation LTA (R2 146)	☐ Source ☐ Inferred	
	☐ Corrective action LTA (R3 147)	☐ Source ☐ Inferred	
	☐ Action not yet started or untimely (R3 148)	☐ Source ☐ Inferred	
	☐ No action planned (R3 149)	☐ Source ☐ Inferred	
	☐ CAP Programmatic deficiency (R4 150)	☐ Source ☐ Inferred	
	☐ Willingness to raise concerns LTA (R5 151)	☐ Source ☐ Inferred	
	☐ Preventing and detecting retaliation LTA (R5 152)	☐ Source ☐ Inferred	
	☐ Failure to resolve known problems in a prompt fashion	☐ Source ☐ Inferred	
	☐ Failure to maintain equipment in accordance with licensing basis	☐ Source ☐ Inferred	
	☐ Audit / self-assessment / effectiveness review LTA (R1 144)	☐ Source ☐ Inferred	
	☐ Other: ______	☐ Source ☐ Inferred	
	☐ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	
Communication	☐ No communication / information not communicated (C 160)	☐ Source ☐ Inferred	
	☐ Misunderstood or misinterpreted information (C 51)	☐ Source ☐ Inferred	

PSF	Negative Contributory Factor	Source / Inference	Comment
	☐ Communication not timely (C 52)	☐ Source ☐ Inferred	
	☐ Communication content less than adequate (LTA) (C 53)	☐ Source ☐ Inferred	
	☐ Communication equipment LTA (C 162)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Environment	☐ Temperature / humidity less than adequate (LTA) (H10 71)	☐ Source ☐ Inferred	
	☐ Lighting LTA (H10 72)	☐ Source ☐ Inferred	
	☐ Noise (H10 73)	☐ Source ☐ Inferred	
	☐ Radiation (H10 74)	☐ Source ☐ Inferred	
	☐ Work area layout or accessibility LTA (H10 75)	☐ Source ☐ Inferred	
	☐ Postings / signs LTA (H10 76)	☐ Source ☐ Inferred	
	☐ Task design / work environment LTA (F 126)	☐ Source ☐ Inferred	
	☐ Fire / smoke	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Team Dynamics / Characteristics	☐ Supervisor too involved in tasks, inadequate oversight	☐ Source ☐ Inferred	
	☐ Crew interaction style not appropriate to the situation	☐ Source ☐ Inferred	
	☐ Team interactions less than adequate (W2 191)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.

Section 5: Performance Shaping Factors

Assign PSF ratings for the subevent. This section summarizes and assigns a PSF level (Insufficient Information, Good, Nominal, Poor) to the detailed performance shaping factor information indicated in Sections 3 and 4. Leave a detailed comment, with reference to the appropriate details sections.

PSF	PSF Level	Comment
Available Time	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Stress & Stressors	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Complexity	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Experience & Training	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Procedures & Reference Documents	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Ergonomics& HMI	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Fitness for Duty / Fatigue	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Work Processes	☐Insufficient Information ☐Good ☐Nominal ☒Poor	Overall work processes were poor. See section 4.
Planning / Scheduling	☐Insufficient Information ☐Good ☐Nominal ☒Poor	Management policy of allowing a 25% grace period on preventative maintenance contributed to lack of maintenance.
Supervision / Management	☐Insufficient Information ☐Good ☐Nominal ☒Poor	Inadequate oversight of maintenance personnel. Poor emphasis on safety.
Conduct of Work	☐Insufficient Information ☐Good ☐Nominal ☒Poor	Maintenance personnel did not follow established modification process or consult vendor manual.
Problem Identification & Resolution (PIR) / Corrective Action Plan (CAP)	☐Insufficient Information ☐Good ☐Nominal ☒Poor	CTG 11-1 exceeded allowable failures on demand for several years. Management failed to implement preventative measures to ensure that CTG 11-1 would start on demand.
Communication	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Environment	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Team Dynamics / Characteristics	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.

Section 6: Human Cognition

Part A: Human Information Processing

Indicate whether the error or success occurred in detection, interpretation, planning, action, a combination (check all that apply), or could not be determined from the source information.

Step		Comment
Detection: Detection or recognition of a stimulus (e.g., a problem, alarm, etc.)	☐ Correct detection ☐ Correct detection based on incorrect information ☒ Incorrect detection ☐ Not Applicable / Insufficient Information	Personnel did not detect that set point needed to be changed.
Interpretation: Interpretation of the stimulus (e.g., understanding the meaning of the stimulus)	☐ Correct interpretation ☐ Correct interpretation based on incorrect detection ☐ Incorrect interpretation ☒ Not Applicable / Insufficient Information	Does not apply
Planning: Planning a response to the stimulus	☐ Correct planning ☒ Correct plan based on incorrect interpretation / detection ☐ Incorrect plan ☐ Not Applicable / Insufficient Information	Did not know they needed to update the set point, so they correctly did not plan to change it.
Action: Executing the planned response	☐ Correct action ☒ Correct action based on incorrect plan / interpretation / detection ☐ Incorrect action ☐ Not Applicable / Insufficient Information	Did not know they needed to update the set point, so they correctly did not change it.
Indeterminate	☐ Indeterminate	

Part B: Cognitive Level
Indicate whether the human activity involved in this subevent was skill-based, rule-based, knowledge-based, or could not be determined from the source information.

	Activity Type		Comment
☐	**Skill-Based:** Routine, highly-practiced task, carried out in a largely automatic fashion, with occasional conscious checks on progress.	☐Correct ☐Incorrect	
☐	**Rule-Based:** Task requires application of memorized or written rules (e.g., if, then), with conscious thinking to verify if the resulting solution is appropriate.	☐Correct ☐Incorrect	
☒	**Knowledge-Based:** Conscious, effortful thought and/or problem solving, often for a novel task or situation.	☐Correct ☒Incorrect	This action needec close attention to procedure and knowledge of interacting component (battery)
☐	**Indeterminate**		

Section 7: Error Type ☐ Check to Exclude

Code for XHE only. Indicate the appropriate error type for any human errors (XHEs). Leave a detailed comment, with reference to the source document. This list continues on the next page.

Part A: Commission / Omission *(Select one.)*

	Error Type	Comment
☐	**Error of Commission:** An incorrect, unintentional, or unplanned action is an error of commission.	
☒	**Error of Omission:** Failure to perform an action is an error of omission.	Did not update set points
☐	**Indeterminate**	

Part B: Slip / Lapse / Mistake / Circumvention / Sabotage *(Select all that apply.)*

	Error Type	Comment
☐	**Slip or lapse:** A slip or lapse is an unconscious unintended action or failure to act, resulting from an attention failure or a memory failure in a routine activity. In spite of a good understanding of the system (process, procedure, specific context) and the intention to perform the task correctly, an unconscious unintended action or a failure to act occurs or a wrong reflex or inappropriate instinctive action takes place. If it is not possible to assign one of the subcategories below to indicate the type of slip or miss, then this code is assigned.	
☐	Response implementation error	
☐	Unconscious wrong action or failure to act, wrong reflex, wrong instinctive action	

	Error Type	Comment
☐	Wrong action or lack of action due to omission of intentional check, insufficient degree of attention, unawareness	
☐	Strong habit intrusion, unwanted reversion to earlier plan	
☐	Continuation of habitual sequence of actions	
☐	Failure to act because focal attention is elsewhere, failure to attend to need for change in action sequence	
☐	Omission of intentional check after task interruption	
☐	Interference error between two simultaneous tasks	
☐	Confusion error (wrong component, wrong unit), spatial disorientation (wrong direction), check on wrong object	
☐	Omission of steps or unnecessary repeating of steps in (unconscious) action sequence	
☐	Task sequence reversal error	
☐	If appropriate, check the most applicable characterization of the slip: ☐ too early ☐ too late ☐ too fast ☐ too slow ☐ too hard ☐ too soft ☐ too long ☐ too short ☐ undercorrect ☐ overcorrect ☐ misread	
☐	**Mistake:** A mistake is an intended action resulting in an undesired outcome in a problem solving activity: a person made a wrong action because he did not understand the system, the procedure, the specific context, the prescribed task, etc. Use this category if you cannot distinguish among the mistake examples listed below.	
☐	Misdiagnosis, misinterpretation, situation assessment error	
☐	Wrong mental model, wrong hypothesis	
☐	Failure to detect situation, information overload (indications not noticed, acted upon)	
☐	Use of wrong procedure	
☐	Misunderstood instructions / information	
☐	Lack of specific knowledge	
☐	Tunnel vision (focus on limited number of indications, lack of big picture)	
☐	Over-reliance on favorite indications	
☐	Not believing indications / information (lack of confidence)	
☐	Mindset / preconceived idea / confirmation bias / overconfidence (failure to change opinion, discarding contradictory evidence)	
☐	Over-reliance on expert knowledge	
☐	**Circumvention:** In spite of a good understanding of the system (process, procedure, specific context) an intentional breaking of known rules, prescriptions, etc., occurred without malevolent intention. Use this field if it is clear that a circumvention applies but unclear which of the options below apply.	
☐	Administrative control circumvented or intentionally not performed	
☒	Required procedures, drawings, or other references not used	Did not follow established modification process.
☐	Intentional shortcuts in prescribed task sequence	
☐	Unauthorized material substitution	
☐	Situations that require compromises between system safety and other objectives (production, personal or personnel safety, etc.)	
☐	Intentional disregard of safety prescriptions / concerns	
☐	**Sabotage:** An intentional breaking of known rules, prescriptions, etc., occurred with malevolent intention.	
☐	**Indeterminate**	

Section 8: Subevent Comments

Provide any additional remarks necessary to complete or supplement the worksheet analysis for this subevent.

_____

Human Event Repository & Analysis (HERA) Worksheet, Part B

Source Document: LER50-341-2003-002 Subevent Code: HS1

Description: The inverter had the incorrect low voltage set points for about 6 months until the set point card S2A-167 was changed. During this card replacement, personnel referenced the vendor manual and recognized the 1.75 volt/cell requirement, counted 56 cells on CTG 11-1 and correctly adjusted the low voltage trip set point to 98 volts, installed the card and placed CTG 11-1 in service.

Section 1: Personnel Involved in Subevent

Indicate which personnel were involved in the subevent. Check all that apply.

- ☐ Operations (OPS)
  - ☐ OPS Supervisors
  - ☐ Control Room (CR) Operators
  - ☐ Outside of CR Operators
  - ☐ Technical Support Center (TSC)
- ☐ Maintenance and Testing
  - ☐ Maintenance Supervision / Planning
  - ☒ Mechanical
  - ☐ Electrical
  - ☒ I&C
- ☐ Management
- ☐ Plant Support Personnel
  - ☐ Administrative Support
  - ☐ Chemistry
  - ☐ Emergency Planning / Response
  - ☐ Engineering
  - ☐ Fitness for Duty
  - ☐ Fuel Handling
  - ☐ Health Physics
  - ☐ Procedure Writers
  - ☐ QA / Oversight
- ☐ Site-Wide
  - ☐ Security
  - ☐ Training
  - ☐ Shipping / Transportation
  - ☐ Specialized Task Force
  - ☐ Work Control
  - ☐ Licensing / Regulatory Affairs
- ☐ Non-Plant Personnel
  - ☐ Contractor Personnel
  - ☐ Manufacturer
  - ☐ NRC / Regulator
  - ☐ Vendor
- ☐ Other: _____

Section 2: Plant Conditions

Part A: Contributing Plant Conditions

Indicate plant conditions that contribute to this subevent, and / or influence the decisions and / or actions of personnel. Leave a detailed comment, with reference to the source document.

Plant Condition	Comment
☐ Equipment installed does not meet all codes / requirements	
☐ Manufacturer fabrication / construction inadequate	
☐ Specifications provided by manufacturer inadequate	
☐ Documents, drawings, information, etc., provided by the manufacturer incorrect or inadequate	
☐ Substitute parts / material used do not meet specifications	
☐ Material used inadequate	
☐ QA requirements not used or met during procurement process	
☐ Post-procurement requirements not used / performed	
☐ Lack of proper tools / materials	
☒ Installation workmanship inadequate	Previous installation (XHE1) was incorrect.
☐ Equipment failure / malfunction	
☐ System / train / equipment unavailable	
☐ Instrumentation problems / inaccuracies	
☐ Control problems	
☐ Plant / equipment not in a normal state	
☐ Plant transitioning between power modes	
☐ Loss of electrical power	
☐ Reactor scram / plant transient	
☐ Fire	
☐ Other: _____	
☐ None / Not Applicable / Indeterminate	

Part B: Effects on Plant ☐ Check to Exclude

Indicate the effects of this subevent on the plant.

1. Affected Function(s): Human Performance [D] - Work practices
2. Affected System(s): ACP
3. Affected Component(s): ACP: INV

Section 3: Positive Contributory Factors / PSF Details

Indicate any positive factors beyond what is nominally expected that contributed to the subevent. Check all that apply; if no details apply for a PSF category, check None. Indicate whether the detail is selected based on evidence directly from the source or if it is coder inference. Leave a detailed comment, with reference to the source document. This information is used to calculate the Performance Shaping Factor (PSF) level in Section 5. This table continues on the next page.

PSF	Positive Contributory Factor	Source / Inference	Comment
Available Time	☐ More than sufficient time given the context	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Stress & Stressors	☐ Enhanced alertness / no negative effects	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Complexity	☐ Failures have single vs. multiple effects	☐ Source ☐ Inferred	
	☐ Causal connections apparent	☐ Source ☐ Inferred	
	☐ Dependencies well defined	☐ Source ☐ Inferred	
	☐ Few or no concurrent tasks	☐ Source ☐ Inferred	
	☐ Action straightforward with little to memorize and with no burden	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Experience & Training	☐ Frequently performed / well-practiced task	☐ Source ☐ Inferred	
	☐ Well qualified / trained for task	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Procedures & Reference Documents	☐ Guidance particularly relevant and correctly directed the correct action or response	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Ergonomics & HMI	☐ Unique features of HMI were particularly useful to this situation	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Fitness for Duty / Fatigue	☐ Optimal health / fitness was key to the success	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Work Processes	☐ Other: _____	☐ Source ☐ Inferred	
	☐ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	
Planning / Scheduling	☐ Correct work package development important to the success	☐ Source ☐ Inferred	
	☐ Work planning / staff scheduling important to the success	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Supervision / Management	☐ Clear performance standards	☐ Source ☐ Inferred	
	☐ Supervision properly involved in task	☐ Source ☐ Inferred	
	☐ Supervision alerted operators to key issue that they had missed	☐ Source ☐ Inferred	
	☐ Pre-task briefing focused on failure scenario that actually occurred / discussed response plans that were directly applicable	☐ Source ☐ Inferred	
	☐ Pre-task briefing alerted operators to potential problems in a way that made them alert to the situation that developed	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	

PSF	Positive Contributory Factor	Source / Inference	Comment
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Conduct of Work	☒ Quick identification of key information was important to success	☒ Source ☐ Inferred	Maintenance personnel realized that low set point must be adjusted.
	☐ Error found by 2nd checker, 2nd crew, or 2nd unit	☐ Source ☐ Inferred	
	☐ Important information easily differentiated	☐ Source ☐ Inferred	
	☐ Determining appropriate procedure to use in unique situation was important to success	☐ Source ☐ Inferred	
	☐ Complex system interactions identified and resolved	☐ Source ☐ Inferred	
	☐ Remembered omitted step	☐ Source ☐ Inferred	
	☐ Difficult or potentially confusing situation well understood	☐ Source ☐ Inferred	
	☐ Safety implications identified and understood in a way that was important to success	☐ Source ☐ Inferred	
	☐ Acceptance criteria understood and properly applied to resolve difficult situation	☐ Source ☐ Inferred	
	☐ Proper post-modification testing identified and ensured resolution of significant problem	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☐ None / Not Applicable / Indeterminate	☐ Source ☐ Inferred	
Problem Identification & Resolution (PIR) / Corrective Action Plan (CAP)	☐ Good trending of problems was important in correct diagnosis / response plan revision	☐ Source ☐ Inferred	
	☐ Adaptation of industry notices / practices was key to correct diagnosis / response plan verification	☐ Source ☐ Inferred	
	☐ Good corrective action plan avoided serious problems	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Communication	☐ Communications practice was key to avoiding severe difficulties	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Environment	☐ Environment particularly important to success	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.
Team Dynamics / Characteristics	☐ Extraordinary teamwork and / or sharing of work assignments was important to success	☐ Source ☐ Inferred	
	☐ Exceptional coordination / communications clarified problems during event	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a positive factor.

Section 4: Negative Contributory Factors / PSF Details

Indicate any negative factors that contributed to the subevent. Check all that apply; if no details apply for a PSF category, check None. Indicate whether the detail is selected based on evidence directly from the source or if it is coder inference. Leave a detailed comment, with reference to the source document. This information is used to calculate the Performance Shaping Factor (PSF) level in Section 5. This table continues over the next three pages.

PSF	Negative Contributory Factor	Source / Inference	Comment
Available Time	☐ Limited time to focus on tasks	☐ Source ☐ Inferred	
	☐ Time pressure to complete task	☐ Source ☐ Inferred	
	☐ Inappropriate balance between available and required time	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Stress & Stressors	☐ High stress	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Complexity	☐ High number of alarms	☐ Source ☐ Inferred	
	☐ Ambiguous or misleading information present	☐ Source ☐ Inferred	
	☐ Information fails to point directly to the problem	☐ Source ☐ Inferred	
	☐ Difficulties in obtaining feedback	☐ Source ☐ Inferred	
	☐ General ambiguity of the event	☐ Source ☐ Inferred	

PSF	Negative Contributory Factor	Source / Inference	Comment
	☐ Extensive knowledge regarding the physical layout of the plant is required	☐ Source ☐ Inferred	
	☐ Coordination required between multiple people in multiple locations	☐ Source ☐ Inferred	
	☐ Scenario demands that the operator combine information from different parts of the process and information systems	☐ Source ☐ Inferred	
	☐ Worker distracted / interrupted (W2 198)	☐ Source ☐ Inferred	
	☐ Demands to track and memorize information	☐ Source ☐ Inferred	
	☐ Problems in differentiating important from less important information	☐ Source ☐ Inferred	
	☐ Simultaneous tasks with high attention demands	☐ Source ☐ Inferred	
	☐ Components failing have multiple versus single effects	☐ Source ☐ Inferred	
	☐ Weak causal connections exist	☐ Source ☐ Inferred	
	☐ Loss of plant functionality complicates recovery path	☐ Source ☐ Inferred	
	☐ System dependencies are not well defined	☐ Source ☐ Inferred	
	☐ Presence of multiple faults	☐ Source ☐ Inferred	
	☐ Simultaneous maintenance tasks required or planned	☐ Source ☐ Inferred	
	☐ Causes equipment to perform differently during the event	☐ Source ☐ Inferred	
	☐ Subevent contributes to confusion in understanding the event	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Experience & Training	☐ Fitness for Duty (FFD) training missing / less than adequate (LTA) (F 124)	☐ Source ☐ Inferred	
	☐ Training LTA (T 100)	☐ Source ☐ Inferred	
	☐ Training process problem (T 101)	☐ Source ☐ Inferred	
	☐ Individual knowledge problem (T 102)	☐ Source ☐ Inferred	
	☐ Simulator training LTA (T4 103)	☐ Source ☐ Inferred	
	☐ Work practice or craft skill LTA (W2 188)	☐ Source ☐ Inferred	
	☐ Not familiar with job performance standards	☐ Source ☐ Inferred	
	☐ Not familiar / well practiced with task	☐ Source ☐ Inferred	
	☐ Not familiar with tools	☐ Source ☐ Inferred	
	☐ Not qualified for assigned task	☐ Source ☐ Inferred	
	☐ Training incorrect	☐ Source ☐ Inferred	
	☐ Situation outside the scope of training	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Procedures & Reference Documents	☐ No procedure / reference documents (P 110)	☐ Source ☐ Inferred	
	☐ Procedure / reference document technical content less than adequate (LTA) (P 111)	☐ Source ☐ Inferred	
	☐ Procedure / reference document contains human factors deficiencies (P 112)	☐ Source ☐ Inferred	
	☐ Procedure / reference document development and maintenance LTA (P 113)	☐ Source ☐ Inferred	
	☐ Procedures do not cover situation	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Ergonomics & HMI	☐ Alarms / annunciators less than adequate (LTA) (H1)	☐ Source ☐ Inferred	
	☐ Controls / input devices LTA (H2)	☐ Source ☐ Inferred	
	☐ Displays LTA (H3)	☐ Source ☐ Inferred	
	☐ Panel or workstation layout LTA (H4)	☐ Source ☐ Inferred	
	☐ Equipment LTA (H5)	☐ Source ☐ Inferred	
	☐ Tools and materials LTA (H6)	☐ Source ☐ Inferred	
	☐ Labels LTA (H7)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Fitness for Duty / Fatigue	☐ Working continuously for considerable number of hours	☐ Source ☐ Inferred	
	☐ Working without rest day for considerable time	☐ Source ☐ Inferred	
	☐ Unfamiliar work cycle	☐ Source ☐ Inferred	
	☐ Frequent changes of shift	☐ Source ☐ Inferred	
	☐ Problem related to night work	☐ Source ☐ Inferred	

PSF	Negative Contributory Factor	Source / Inference	Comment
	☐ Circadian factors / individual differences (F 127)	☐ Source ☐ Inferred	
	☐ Impairment (F 129)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Work Processes	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Planning / Scheduling	☐ Work planning does not control excessive continuous working hours (F 125)	☐ Source ☐ Inferred	
	☐ Inadequate staffing / task allocation (W1 181)	☐ Source ☐ Inferred	
	☐ Scheduling and planning less than adequate (LTA) (W1 180)	☐ Source ☐ Inferred	
	☐ Work package quality LTA (W1 182)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Supervision / Management	☐ Administrative assurance of personnel ability and qualification to perform work less than adequate (LTA) (F 120-122)	☐ Source ☐ Inferred	
	☐ Inadequate supervision / command and control (O1 130)	☐ Source ☐ Inferred	
	☐ Management expectations or directions less than adequate (O1 131)	☐ Source ☐ Inferred	
	☐ Duties and tasks not clearly explained / work orders not clearly given	☐ Source ☐ Inferred	
	☐ Progress not adequately monitored	☐ Source ☐ Inferred	
	☐ Inadequate control of contractors	☐ Source ☐ Inferred	
	☐ Frequent task re-assignment	☐ Source ☐ Inferred	
	☐ Pre-job activities (e.g., pre-job briefing) LTA (W1 183)	☐ Source ☐ Inferred	
	☐ Safety aspects of task not emphasized	☐ Source ☐ Inferred	
	☐ Informally sanctioned by management	☐ Source ☐ Inferred	
	☐ Formally sanctioned workarounds cause problem	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Conduct of Work	☐ Self-check less than adequate (LTA) (W2 197)	☐ Source ☐ Inferred	
	☐ Improper tools or materials selected / provided / used	☐ Source ☐ Inferred	
	☐ Necessary tools / materials not provided or used	☐ Source ☐ Inferred	
	☐ Information present but not adequately used	☐ Source ☐ Inferred	
	☐ Failure to adequately coordinate multiple tasks / task partitioning / interruptions	☐ Source ☐ Inferred	
	☐ Fitness for Duty self-declaration LTA (F 123)	☐ Source ☐ Inferred	
	☐ Fitness for Duty non-compliance (F 128)	☐ Source ☐ Inferred	
	☐ Control room sign off on maintenance not performed	☐ Source ☐ Inferred	
	☐ Tag outs LTA (W1 184)	☐ Source ☐ Inferred	
	☐ Second independent checker not used or available	☐ Source ☐ Inferred	
	☐ Work untimely (e.g., too long, late) (W2 192)	☐ Source ☐ Inferred	
	☐ Housekeeping LTA (W2 194)	☐ Source ☐ Inferred	
	☐ Logkeeping or log review LTA (W2 195)	☐ Source ☐ Inferred	
	☐ Independent verification / plant tours LTA (W2 196)	☐ Source ☐ Inferred	
	☐ Procedural adherence LTA (W2 185)	☐ Source ☐ Inferred	
	☐ Failure to take action / meet requirements (W2 186)	☐ Source ☐ Inferred	
	☐ Action implementation LTA (W2 187)	☐ Source ☐ Inferred	
	☐ Recognition of adverse condition / questioning LTA (W2 189)	☐ Source ☐ Inferred	
	☐ Failure to stop work / non conservative decision making (W2 190)	☐ Source ☐ Inferred	
	☐ Non-conservative action (W2 193)	☐ Source ☐ Inferred	
	☐ Failure to apply knowledge	☐ Source ☐ Inferred	
	☐ Failure to access available sources of information	☐ Source ☐ Inferred	
	☐ Post-modification testing inadequate	☐ Source ☐ Inferred	
	☐ Post-maintenance testing inadequate	☐ Source ☐ Inferred	
	☐ Retest requirements not specified	☐ Source ☐ Inferred	
	☐ Retest delayed	☐ Source ☐ Inferred	
	☐ Test acceptance criteria inadequate	☐ Source ☐ Inferred	

PSF	Negative Contributory Factor	Source / Inference	Comment
	☐ Test results review inadequate	☐ Source ☐ Inferred	
	☐ Surveillance schedule not followed	☐ Source ☐ Inferred	
	☐ Situational surveillance not performed	☐ Source ☐ Inferred	
	☐ Required surveillance / test not scheduled	☐ Source ☐ Inferred	
	☐ Incorrect parts / consumables installed / used	☐ Source ☐ Inferred	
	☐ Failure to exclude foreign material	☐ Source ☐ Inferred	
	☐ Incorrect restoration of plant following maintenance / isolation / testing	☐ Source ☐ Inferred	
	☐ Independent decision to perform work around or circumvention	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Problem Identification & Resolution (PIR) / Corrective Action Plan (CAP)	☐ Problem not completely or accurately identified (R1 140)	☐ Source ☐ Inferred	
	☐ Problem not properly classified or prioritized (R1 141)	☐ Source ☐ Inferred	
	☐ Operating experience review less than adequate (LTA) (R1 142)	☐ Source ☐ Inferred	
	☐ Failures to respond to industry notices or follow industry practices	☐ Source ☐ Inferred	
	☐ Tracking / trending LTA (R1 143)	☐ Source ☐ Inferred	
	☐ Root cause development LTA (R2 145)	☐ Source ☐ Inferred	
	☐ Evaluation LTA (R2 146)	☐ Source ☐ Inferred	
	☐ Corrective action LTA (R3 147)	☐ Source ☐ Inferred	
	☐ Action not yet started or untimely (R3 148)	☐ Source ☐ Inferred	
	☐ No action planned (R3 149)	☐ Source ☐ Inferred	
	☐ CAP Programmatic deficiency (R4 150)	☐ Source ☐ Inferred	
	☐ Willingness to raise concerns LTA (R5 151)	☐ Source ☐ Inferred	
	☐ Preventing and detecting retaliation LTA (R5 152)	☐ Source ☐ Inferred	
	☐ Failure to resolve known problems in a prompt fashion	☐ Source ☐ Inferred	
	☐ Failure to maintain equipment in accordance with licensing basis	☐ Source ☐ Inferred	
	☐ Audit / self-assessment / effectiveness review LTA (R1 144)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Communication	☐ No communication / information not communicated (C 160)	☐ Source ☐ Inferred	
	☐ Misunderstood or misinterpreted information (C 51)	☐ Source ☐ Inferred	
	☐ Communication not timely (C 52)	☐ Source ☐ Inferred	
	☐ Communication content less than adequate (LTA) (C 53)	☐ Source ☐ Inferred	
	☐ Communication equipment LTA (C 162)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Environment	☐ Temperature / humidity less than adequate (LTA) (H10 71)	☐ Source ☐ Inferred	
	☐ Lighting LTA (H10 72)	☐ Source ☐ Inferred	
	☐ Noise (H10 73)	☐ Source ☐ Inferred	
	☐ Radiation (H10 74)	☐ Source ☐ Inferred	
	☐ Work area layout or accessibility LTA (H10 75)	☐ Source ☐ Inferred	
	☐ Postings / signs LTA (H10 76)	☐ Source ☐ Inferred	
	☐ Task design / work environment LTA (F 126)	☐ Source ☐ Inferred	
	☐ Fire / smoke	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.
Team Dynamics / Characteristics	☐ Supervisor too involved in tasks, inadequate oversight	☐ Source ☐ Inferred	
	☐ Crew interaction style not appropriate to the situation	☐ Source ☐ Inferred	
	☐ Team interactions less than adequate (W2 191)	☐ Source ☐ Inferred	
	☐ Other: _____	☐ Source ☐ Inferred	
	☒ None / Not Applicable / Indeterminate	☒ Source ☐ Inferred	Nothing in the source indicates that this was a negative factor.

Section 5: Performance Shaping Factors

Assign PSF ratings for the subevent. This section summarizes and assigns a PSF level (Insufficient Information, Good, Nominal, Poor) to the detailed performance shaping factor information indicated in Sections 3 and 4. Leave a detailed comment, with reference to the appropriate details sections.

PSF	PSF Level	Comment
Available Time	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Stress & Stressors	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Complexity	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Experience & Training	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Procedures & Reference Documents	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Ergonomics& HMI	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Fitness for Duty / Fatigue	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Work Processes	☐Insufficient Information ☒Good ☐Nominal ☐Poor	
Planning / Scheduling	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Supervision / Management	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Conduct of Work	☐Insufficient Information ☒Good ☐Nominal ☐Poor	Maintenance personnel correctly identified need to update set points.
Problem Identification & Resolution (PIR) / Corrective Action Plan (CAP)	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Communication	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Environment	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.
Team Dynamics / Characteristics	☒Insufficient Information ☐Good ☐Nominal ☐Poor	Insufficient information.

Section 6: Human Cognition

Part A: Human Information Processing

Indicate whether the error or success occurred in detection, interpretation, planning, action, a combination (check all that apply), or could not be determined from the source information.

Step		Comment
Detection: Detection or recognition of a stimulus (e.g., a problem, alarm, etc.)	☒ Correct detection ☐ Correct detection based on incorrect information ☐ Incorrect detection ☐ Not Applicable / Insufficient Information	Personnel correctly matched maintenance procedure requirements with actual hardware.
Interpretation: Interpretation of the stimulus (e.g., understanding the meaning of the stimulus)	☒ Correct interpretation ☐ Correct interpretation based on incorrect detection ☐ Incorrect interpretation ☐ Not Applicable / Insufficient Information	Personnel correctly resolved setpoint calculation.
Planning: Planning a response to the stimulus	☒ Correct planning ☐ Correct plan based on incorrect interpretation / detection ☐ Incorrect plan ☐ Not Applicable / Insufficient Information	Personnel correctly planned response.
Action: Executing the planned response	☒ Correct action ☐ Correct action based on incorrect plan / interpretation / detection ☐ Incorrect action ☐ Not Applicable / Insufficient Information	Personnel correctly executed proper setpoints.
Indeterminate	☐ Indeterminate	

Part B: Cognitive Level
Indicate whether the human activity involved in this subevent was skill-based, rule-based, knowledge-based, or could not be determined from the source information.

	Activity Type		Comment
☐	**Skill-Based:** Routine, highly-practiced task, carried out in a largely automatic fashion, with occasional conscious checks on progress.	☐Correct ☐Incorrect	
☐	**Rule-Based:** Task requires application of memorized or written rules (e.g., if, then), with conscious thinking to verify if the resulting solution is appropriate.	☐Correct ☐Incorrect	
☒	**Knowledge-Based:** Conscious, effortful thought and/or problem solving, often for a novel task or situation.	☒Correct ☐Incorrect	Action required knowledge of related components in system.
☐	**Indeterminate**		

Section 7: Error Type ☒ Check to Exclude

Code for XHE only. Indicate the appropriate error type for any human errors (XHEs). Leave a detailed comment, with reference to the source document. This list continues on the next page.

Part A: Commission / Omission *(Select one.)*

	Error Type	Comment
☐	**Error of Commission:** An incorrect, unintentional, or unplanned action is an error of commission.	
☐	**Error of Omission:** Failure to perform an action is an error of omission.	
☐	**Indeterminate**	

Part B: Slip / Lapse / Mistake / Circumvention / Sabotage *(Select all that apply.)*

	Error Type	Comment
☐	**Slip or lapse:** A slip or lapse is an unconscious unintended action or failure to act, resulting from an attention failure or a memory failure in a routine activity. In spite of a good understanding of the system (process, procedure, specific context) and the intention to perform the task correctly, an unconscious unintended action or a failure to act occurs or a wrong reflex or inappropriate instinctive action takes place. If it is not possible to assign one of the subcategories below to indicate the type of slip or miss, then this code is assigned.	
☐	Response implementation error	
☐	Unconscious wrong action or failure to act, wrong reflex, wrong instinctive action	
☐	Wrong action or lack of action due to omission of intentional check, insufficient degree of attention, unawareness	
☐	Strong habit intrusion, unwanted reversion to earlier plan	
☐	Continuation of habitual sequence of actions	
☐	Failure to act because focal attention is elsewhere, failure to attend to need for change in action sequence	
☐	Omission of intentional check after task interruption	
☐	Interference error between two simultaneous tasks	
☐	Confusion error (wrong component, wrong unit), spatial disorientation (wrong direction), check on wrong object	
☐	Omission of steps or unnecessary repeating of steps in (unconscious) action sequence	
☐	Task sequence reversal error	
☐	If appropriate, check the most applicable characterization of the slip: ☐ too early ☐ too late ☐ too fast ☐ too slow ☐ too hard ☐ too soft ☐ too long ☐ too short ☐ undercorrect ☐ overcorrect ☐ misread	
☐	**Mistake:** A mistake is an intended action resulting in an undesired outcome in a problem solving activity: a person made a wrong action because he did not understand the system, the procedure, the specific context, the prescribed task, etc. Use this category if you cannot distinguish among the mistake examples listed below.	
☐	Misdiagnosis, misinterpretation, situation assessment error	
☐	Wrong mental model, wrong hypothesis	
☐	Failure to detect situation, information overload (indications not noticed, acted upon)	
☐	Use of wrong procedure	
☐	Misunderstood instructions / information	
☐	Lack of specific knowledge	
☐	Tunnel vision (focus on limited number of indications, lack of big picture)	
☐	Over-reliance on favorite indications	
☐	Not believing indications / information (lack of confidence)	

	Error Type	Comment
☐	Mindset / preconceived idea / confirmation bias / overconfidence (failure to change opinion, discarding contradictory evidence)	
☐	Over-reliance on expert knowledge	
☐	**Circumvention:** In spite of a good understanding of the system (process, procedure, specific context) an intentional breaking of known rules, prescriptions, etc., occurred without malevolent intention. Use this field if it is clear that a circumvention applies but unclear which of the options below apply.	
☐	Administrative control circumvented or intentionally not performed	
☐	Required procedures, drawings, or other references not used	
☐	Intentional shortcuts in prescribed task sequence	
☐	Unauthorized material substitution	
☐	Situations that require compromises between system safety and other objectives (production, personal or personnel safety, etc.)	
☐	Intentional disregard of safety prescriptions / concerns	
☐	**Sabotage:** An intentional breaking of known rules, prescriptions, etc., occurred with malevolent intention.	
☐	**Indeterminate**	

Section 8: Subevent Comments

Provide any additional remarks necessary to complete or supplement the worksheet analysis for this subevent.

Appendix B

PSF Mapping

Appendix B demonstrates how the proposed PSF hierarchy relates to current PSF sets. PSFs from the NRC's Good Practices for HRA [39] are mapped onto the new framework. A "PSF-superset" is also mapped onto the new framework. This "PSF-superset" contains all PSFs identified during a workshop attended by over 20 international HRA experts [44].

	Proposed PSF Set	**NRC “Good Practices for HRA” PSF**	**Expert Workshop PSFs**
1. Situation	1.1. External Environment	Environment in Which the Action Needs To Be Performed	Physical environment
	1.2. Hardware & Software Conditions	Operability of the Equipment To Be Manipulated	Facility/plant conditions; equipment state indication; erroneous info;
	1.3. Task Load	Time Available and Time Required to Complete the Act, Including the Impact of Concurrent and Competing Activities; Workload	Task requirements
	1.4. Time Load		Time availability
	1.5. Other Loads		Distractions; parallel tasks
	1.5.1.Non-task Load		Parallel tasks
	1.5.2.Passive Information Load		Distractions
	1.6. Task Complexity	Complexity of the Required Diagnosis and Response, the Need for Special Sequencing, and the Familiarity of the Situation	Complexity
	1.6.1.Cognitive		
	1.6.2.Execution		
2. Stressors	2.1. Perceived Situation:	Stress	
	2.1.1.Severity		Risk
	2.1.2.Urgency	Time Pressure, and Stress	Risk, Perceived time available
	2.2. Perceived Decision:	Stress	Risk
	2.2.1.Responsibility		Personal risk
	2.2.2.Impact		Risk
	2.2.2.1. Personal		Personal Risk
	2.2.2.2. Plant		Risk
	2.2.2.3. Society		Risk
3. Machine	3.1. HSI	Ergonomic Quality of the Human-System Interface (HSI)	Ergonomics, HMI design, accessibility, and control
	3.1.1.Input	Accessability and Operability of the Equipment To Be Manipulated	
	3.1.2.Output	Availability and Clarity of Instrumentation (Cues to Take Actions and Confirm Expected Plant Response)	Plant info provided, Stimulus quality,
	3.2. System Responses	Consideration of “Realistic” Accident Sequence Diversions and Deviation	Expectations; misleading information
	3.2.1.Ambiguity		Misleading information
4. Team	4.1. Communication	Communications	Communication
	4.1.1.Availability		
	4.1.2.Quality		
	4.2. Direct Supervision	Team/Crew Dynamics and Crew Characteristics	Leadership, leadership style; supervision

	4.2.1. Leadership	Communications	Protocols for communication and proc use; Protocols for communication and proc use
	4.2.2. Team Membership	B.7 Team/Crew Dynamics and Crew Characteristics [Degree of Independence Among Individuals, Operator Attitudes/Biases/Rules, Use of Status Checks, Approach for Implementing Procedures]	Monitoring; verification, crew dynamics
	4.3. Team Coordination		Division of Work, crew dynamics and aggressiveness/speed, consultation
	4.4. Team Cohesion		Crew dynamics
	4.5. Role Awareness		Roles; responsibilities
5. Organization	5.1. Programs	Suitability of Relevant Procedures and Administrative Controls	
	5.1.1. Training	Applicability and Suitability of Training/Experience	Training, trained responses; practice
	5.1.1.1. Quality		
	5.1.1.2. Availability		
	5.1.2. Corrective Action Program	Suitability of Administrative Controls	
	5.1.2.1. Quality		
	5.1.2.2. Availability		
	5.1.3. Other Programs		
	5.1.3.1. Quality		
	5.1.3.2. Availability		
	5.2. Safety Culture		Questioning attitude; operational safety culture
	5.3. Management Work Practices		
	5.3.1. Staffing	Available Staffing/Resources	Staffing; team/crew composition
	5.3.1.1. Number		
	5.3.1.2. Qualification		
	5.3.1.3. Team		team/crew composition
	5.3.2. Scheduling		Scheduling
	5.3.2.1. Prioritization		
	5.3.2.2. Frequency		
	5.3.3. Compliance	Suitability of Administrative Controls	
	5.4. Workplace adequacy		Physical environment, ergonomics, available resources
	5.5. Resources	Suitability of Relevant Procedures and Administrative Controls	Available resources
	5.5.1. Tools	Need for Special Tools (Keys, Ladders, Hoses, Clothing Such as To Enter a Radiation Area)	Tools, job aids
	5.5.2. Procedures	Suitability of Relevant	Procedural Guidance

	5.5.3. Information pertinent to task	Procedures and Administrative Controls	Job aids; cognitive artifacts?; knowledge resources
6. Person	6.1. Attention to:	Special Fitness Needs, Consideration of “Realistic” Accident Sequence Diversions and Deviations	
	6.1.1. Task		Attention; distractions
	6.1.2. Surroundings		Situational Awareness
	6.2. Physical & Psychological Abilities		Available cognitive resources; physical ability/stature
	6.2.1. Alertness		Alertness
	6.2.2. Fatigue		fatigue
	6.2.3. Impairment		
	6.2.4. Sensory Limits		Sensory Limits, Filtering
	6.2.5. Other		
	6.3. Bias	Familiarity of the Situation	Anticipation sets, scripts, schema; Learned patterns; recency; conditioning; expectations, heuristics, informal rules, mental models; conditioning; rules; common practice; past plant/industry performance
	6.4. Morale/motivation/attitude	Special Fitness Needs	Goals & Motivation
	6.4.1. Compliance	Crew Characteristics	Shortcuts
	6.4.2. Prioritization		Resource allocation; Prioritization
	6.4.2.1. Conflicting goals		Conflicting goals; Conflicts; Double bind; Scheduling, interruptions
	6.4.2.2. Task order		
	6.4.3. Information Use		Implementation of procedure
	6.4.4. Problem Solving Style		
	6.5. Knowledge & Experience	Applicability and Suitability of Training/Experience; Familiarity of the Situation	Experience; knowledge resources
	6.6. Skills		Practice?
	6.7. Familiarity with Situation	Familiarity of the Situation	Experience, recency, familiarity with situation; practice; past plant/industry performance

Appendix C

Quantitative Analysis in R

Appendix C provides the computer code used to evaluate the models in R [127]. The code runs a polychoric correlation analysis and then runs different sized factor Minres and Principal Axes factor analysis models.

```
library(nFactors)
library(polycor) # Calls package to perform polychoric correlation
library(psych) # Calls package to perform Factor Analysis
options(digits=2) # Limits number of decimal places displayed

recodeddata<- data.frame(Training, SCMgmtCAP, Resources, Team, Attitude,
KnowSkillPPA, HSISysResponses, LoadsPercept, EventComplex)
#these are the variables in the 9-bubble model

NPSFs <- dim(recodeddata)[2]
#Obtains number of PSFs; used to determine size of correlation matrix

thenames <- list(names(recodeddata), names(recodeddata))
#Obtains list of PSF names

results <- matrix(0, NPSFs, NPSFs, dimnames=thenames)
#Creates empty (NPSFs x NPSFs) matrix for storing correlations

# this will get all of the polychoric correlations of the items
for(i in 1:NPSFs){
for(j in 1:NPSFs){
Corresults[i,j] <- polychor(recodeddata[,i], recodeddata[,j])
}
}
eigen(results)

#Single factor model:
factor.pa(Corresults, nfactors=1, residuals = FALSE, rotate = "none",
n.obs=158, min.err=0.001, digits=3, max.iter=5000)
```

```
#Two factor model:
factor.minres(Corresults, nfactors=2, residuals = FALSE, rotate = "none",
n.obs=158, min.err=0.001, digits=3, max.iter=5000)

#Three factor model:
factor.minres(Corresults, nfactors=3, residuals = FALSE, rotate = "none",
n.obs=158, min.err=0.001, digits=3, max.iter=5000)

#Four factor model:
factor.minres(Corresults, nfactors=4, residuals = FALSE, rotate = "none",
n.obs=158, min.err=0.001, digits=3, max.iter=5000)

#Five factor model:
factor.minres(Corresults, nfactors=5, residuals = FALSE, rotate = "none",
n.obs=158, min.err=0.001, digits=3, max.iter=5000)

#Four factor model, Varimax (orthogonal) rotation:
factor.minres(Corresults, nfactors=4, residuals = FALSE, rotate = "Varimax",
n.obs=158, min.err=0.001, digits=3, max.iter=5000)

#Four factor model, Promax (oblique) rotation:
factor.pa(Corresults, nfactors=4, residuals = FALSE, rotate = "Promax",
n.obs=158, min.err=0.001, digits=3, max.iter=5000)
```

Appendix D

Raw Data Used to Develop the 9-Bubble model

This appendix contains the raw data used for the analysis and quantification for the 9-Bubble Model. Each row of the table is a single sub-event. The identifying information about the sub-events has been removed and replaced with a generic sub-event number. A value of 1 signifies a Less Than Adequate (LTA) state of the PSF and a value of 0 represents a nominal, indeterminate or adequate PSF state.

	Training	SCMgmtCAP	Resources	Team	Attitude	KnowSkillPPA	HSISysResponses	LoadPercept	EventComplex
Sub-event 1	0	0	1	1	0	1	0	1	1
Sub-event 2	1	0	1	1	1	1	0	1	1
Sub-event 3	0	0	0	0	1	1	0	0	0
Sub-event 4	0	0	0	1	1	0	0	0	0
Sub-event 5	0	0	0	0	0	1	0	0	0
Sub-event 6	1	0	0	1	1	1	0	1	1
Sub-event 7	1	0	0	0	0	1	0	0	1
Sub-event 8	1	0	0	0	0	1	0	0	1
Sub-event 9	0	0	1	0	1	1	0	1	1
Sub-event 10	0	0	0	1	1	1	0	1	1
Sub-event 11	0	0	0	1	1	1	0	1	1
Sub-event 12	0	1	1	1	0	1	0	0	0
Sub-event 13	0	0	0	1	0	1	0	0	1
Sub-event 14	1	1	1	1	0	1	0	1	0
Sub-event 15	1	0	0	1	0	1	0	1	0
Sub-event 16	0	1	0	1	0	1	0	0	0

Sub-event 17	0	0	0	0	0	1	0	0	1
Sub-event 18	1	1	1	1	0	0	0	1	1
Sub-event 19	1	1	1	1	1	1	0	1	1
Sub-event 20	1	1	1	1	1	0	0	1	1
Sub-event 21	1	0	1	1	0	1	0	1	1
Sub-event 22	0	1	0	1	1	0	0	1	0
Sub-event 23	1	0	1	1	1	1	1	1	1
Sub-event 24	1	1	0	0	1	0	1	0	0
Sub-event 25	0	0	0	1	0	1	0	1	1
Sub-event 26	1	0	1	1	0	1	0	0	1
Sub-event 27	0	1	1	1	0	1	0	0	1
Sub-event 28	0	0	1	1	1	1	0	1	1
Sub-event 29	0	1	1	0	1	0	0	0	0
Sub-event 30	0	1	0	0	0	1	0	0	0
Sub-event 31	0	1	0	1	1	1	0	0	0
Sub-event 32	0	1	0	1	1	0	0	0	0
Sub-event 33	0	0	0	1	1	0	0	0	1
Sub-event 34	0	1	1	0	1	1	0	1	1
Sub-event 35	0	0	0	0	1	1	1	0	0
Sub-event 36	0	0	1	0	0	1	0	0	0
Sub-event 37	0	1	1	0	1	1	0	0	0
Sub-event 38	0	1	1	0	1	0	0	0	0
Sub-event 39	0	0	0	0	1	1	0	0	1
Sub-event 40	0	0	1	0	1	0	0	0	1
Sub-event 41	0	0	0	0	0	1	0	0	0
Sub-event 42	0	1	0	0	1	0	0	0	1
Sub-event 43	0	0	0	0	1	0	0	0	0
Sub-event 44	1	0	0	1	1	0	0	1	0
Sub-event 45	0	0	1	0	1	0	0	0	0
Sub-event 46	0	0	1	0	1	1	0	0	0
Sub-event 47	0	0	0	0	0	0	0	0	0
Sub-event 48	0	1	0	0	1	0	0	0	1
Sub-event 49	0	0	1	0	1	1	0	0	0
Sub-event 50	1	1	1	1	1	0	1	1	0
Sub-event 51	1	1	1	1	1	0	0	1	1
Sub-event 52	1	0	1	1	1	0	0	0	1
Sub-event 53	1	1	1	1	1	0	0	0	1
Sub-event 54	1	1	1	0	1	0	0	0	1
Sub-event 55	1	1	1	1	1	0	0	0	1
Sub-event 56	1	0	1	1	1	0	0	0	1
Sub-event 57	1	1	1	1	1	0	0	0	1
Sub-event 58	0	1	0	1	1	0	0	1	0

Sub-event 59	0	1	0	1	1	0	0	1	0
Sub-event 60	0	1	0	0	1	1	0	0	0
Sub-event 61	0	0	0	0	1	1	0	0	0
Sub-event 62	0	0	0	1	1	0	1	0	0
Sub-event 63	0	1	0	0	0	0	1	0	1
Sub-event 64	0	1	0	1	1	1	0	0	0
Sub-event 65	0	1	0	1	1	0	0	0	0
Sub-event 66	1	1	1	1	1	0	0	1	0
Sub-event 67	1	1	1	1	1	0	0	1	0
Sub-event 68	1	1	0	1	1	0	0	1	0
Sub-event 69	0	1	0	1	1	1	0	0	0
Sub-event 70	1	1	0	1	1	1	0	0	0
Sub-event 71	1	0	0	1	0	0	0	1	0
Sub-event 72	1	1	0	1	1	1	0	1	0
Sub-event 73	1	1	1	0	1	1	0	1	1
Sub-event 74	1	1	1	1	1	1	0	1	1
Sub-event 75	1	1	1	1	1	1	0	1	1
Sub-event 76	0	0	1	0	0	0	0	0	0
Sub-event 77	0	1	0	0	1	0	0	0	1
Sub-event 78	0	0	0	1	1	0	0	0	0
Sub-event 79	0	0	1	0	0	0	1	0	0
Sub-event 80	0	0	0	0	1	1	0	1	0
Sub-event 81	0	0	1	0	0	0	0	0	0
Sub-event 82	0	1	1	0	0	1	0	0	0
Sub-event 83	1	1	1	0	1	1	0	0	0
Sub-event 84	1	1	1	0	1	1	0	0	0
Sub-event 85	1	1	0	1	1	1	0	0	0
Sub-event 86	1	1	0	0	0	1	0	0	0
Sub-event 87	1	1	0	0	1	1	0	0	0
Sub-event 88	1	1	0	0	0	1	0	0	0
Sub-event 89	0	1	0	0	1	0	0	0	0
Sub-event 90	0	1	0	0	1	0	0	0	0
Sub-event 91	0	1	0	0	1	0	0	0	0
Sub-event 92	0	1	0	0	0	0	0	0	0
Sub-event 93	0	1	0	0	1	1	0	0	0
Sub-event 94	0	1	0	0	1	0	0	0	0
Sub-event 95	0	1	0	0	1	0	0	0	0
Sub-event 96	1	0	0	0	0	1	1	1	1
Sub-event 97	0	0	0	0	1	0	0	1	0
Sub-event 98	0	0	0	1	0	0	0	1	0
Sub-event 99	0	1	0	0	0	1	0	0	0
Sub-event 100	0	0	0	1	1	1	0	1	0

Sub-event 101	0	0	1	1	1	1	0	1	1
Sub-event 102	0	0	0	0	1	0	0	1	1
Sub-event 103	0	0	1	0	0	1	0	1	1
Sub-event 104	0	0	1	1	0	0	1	1	1
Sub-event 105	1	1	1	0	1	0	0	1	1
Sub-event 106	1	1	0	1	1	1	0	1	1
Sub-event 107	0	0	0	0	1	0	0	1	1
Sub-event 108	0	0	0	1	1	0	0	1	1
Sub-event 109	0	0	0	0	1	0	0	0	0
Sub-event 110	0	1	0	0	0	1	0	0	0
Sub-event 111	0	0	0	0	1	0	0	0	0
Sub-event 112	1	1	1	0	1	0	0	1	1
Sub-event 113	1	0	1	0	1	0	0	1	1
Sub-event 114	1	0	1	0	1	0	0	1	0
Sub-event 115	0	0	0	1	1	1	1	0	1
Sub-event 116	1	0	0	1	0	1	0	0	1
Sub-event 117	1	1	0	0	0	1	0	0	0
Sub-event 118	0	0	0	0	0	1	0	0	0
Sub-event 119	1	0	0	0	0	1	0	0	0
Sub-event 120	1	0	1	0	1	0	0	1	0
Sub-event 121	0	1	0	1	1	0	0	0	0
Sub-event 122	0	1	1	1	1	0	0	0	0
Sub-event 123	0	1	1	0	0	0	0	0	0
Sub-event 124	1	0	1	0	1	0	1	1	1
Sub-event 125	1	0	0	1	0	0	0	0	1
Sub-event 126	0	1	0	0	1	1	0	0	1
Sub-event 127	0	0	0	0	1	0	0	0	0
Sub-event 128	1	0	0	1	0	1	1	1	1
Sub-event 129	0	0	1	0	1	1	0	1	1
Sub-event 130	1	0	0	1	1	0	0	0	0
Sub-event 131	0	1	0	0	0	0	0	0	0
Sub-event 132	0	1	0	0	1	0	0	0	0
Sub-event 133	0	1	0	1	0	0	0	0	0
Sub-event 134	0	1	0	0	0	1	0	0	0
Sub-event 135	0	1	1	0	0	1	0	0	0
Sub-event 136	0	0	0	0	0	1	0	0	1
Sub-event 137	0	0	1	0	0	1	0	0	0
Sub-event 138	0	1	1	0	1	0	0	0	0
Sub-event 139	0	1	1	0	0	1	0	0	0
Sub-event 140	1	0	0	0	1	0	0	1	0
Sub-event 141	1	0	0	0	1	1	0	1	0
Sub-event 142	1	0	1	1	0	0	0	1	0

Sub-event 143	0	0	1	1	0	1	1	0	0
Sub-event 144	0	0	1	1	1	0	1	0	0
Sub-event 145	0	0	1	0	0	1	0	0	0
Sub-event 146	1	1	0	1	0	1	1	1	1
Sub-event 147	1	0	0	1	1	0	0	1	1
Sub-event 148	1	1	0	0	1	1	1	1	0
Sub-event 149	1	1	0	1	0	1	0	1	0
Sub-event 150	1	0	0	0	1	1	1	1	0
Sub-event 151	0	0	0	0	1	1	0	1	0
Sub-event 152	0	0	1	1	1	1	1	1	1
Sub-event 153	0	0	0	0	1	1	1	1	1
Sub-event 154	0	1	0	0	1	1	0	1	0
Sub-event 155	0	0	0	1	1	1	1	1	0
Sub-event 156	0	1	0	0	1	0	0	1	0
Sub-event 157	0	0	0	1	1	0	1	1	1
Sub-event 158	0	0	1	1	1	0	0	0	1
Sum	59	76	63	72	105	83	21	65	62

Table D.1: Raw data used to develop the 9-Bubble Model

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