An Evaluation of Safety and Health Data, with an Emphasis on Developing Performance Measures for Nuclear Chemical Facilities, Using Quantitative and Semi-quantitative Methods

By

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Dedicated with love to my husband, Brandon Lee Fyffe and

written in loving memory of my father, Dr. Scott Ingles Morgan

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NOMENCLATURE

Abbreviation/Symbol	Description
ACC	American Chemistry Council
AHP	Analytical Hierarchy Process
AIB	Accident Investigation Board
AIChE	American Institute of Chemical Engineers
AO	Nuclear Regulatory Commission Abnormal Occurrence Report
APET	Accident Progression Event Tree
ARP/MCU	Actinide Removal Process/Modular Caustic Side-solvent extraction Unit
ASME	American Society of Mechanical Engineers
BLEVE	Boiling Liquid Expanding Vapor Explosion
CAT	Causal Analysis Tree
CCPS	American Institute for Chemical Engineers Center for Chemical Process Safety
CFR	U.S. Code of Federal Regulations
CSB	U.S. Chemical Safety and Hazard Investigation Board
CSTC	DOE Chemical Safety Topical Committee
DART	Days away, restrictions, and transfers rate
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DOE ISM	Department of Energy Integrated Safety Management
DOE EM	Department of Energy Office of Environmental Management
DOT	U.S. Department of Transportation
DSA	Documented Safety Analysis

DWPF	Defense Waste Processing Facility
EFCOG	Energy Facility Contractors Group
EPA	U.S. Environmental Protection Agency
ES&H	Environmental Safety and Health
FAA	Federal Aviation Administration
GAO	Government Accountability Office
HDBK	Handbook
HQ	Headquarters
IAEA	International Atomic Energy Agency
IG	EPA Office of the Inspector General
INPO	Institute for Nuclear Power Operations
IWTU	Integrated Waste Treatment Unit
LCO	Limiting Condition for Operation
LTA	Less than Adequate
MOC	Management of Change
NASA	U.S. National Aeronautics and Space Agency
NNSA	National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
NTSB	National Transportation Safety Board
NUREG	US Nuclear Regulatory Commission Regulation
OE	Operational Emergency
ORPS	Department of Energy Occurrence Reporting and Processing System
OSHA	Occupational Safety and Health Administration
PHA	Process Hazard Analysis
PRA	Probabilistic Risk Assessment

PSM	OSHA's Process Safety Management
RCA	Root Cause Analysis
RFCOP	Revised Fuel Cycle Oversight Process
RMP	EPA Risk Management Plan
SC	Significance Category
SME	Subject Matter Expert
STD	Standard
TRC	Total Recordable Cases
USQ	Unreviewed Safety Question
USQD	Unreviewed Safety Question Determination

EXECUTIVE SUMMARY

The Department of Energy (DOE) has expanded the number of nuclear facilities using chemical processes to complete its waste management mission over the last decade. Recent facilities included the Actinide Removal Process/Modular Caustic Side-solvent extraction Unit (ARP/MCU) at Savannah River, the processing plants for the deconversion of depleted uranium hexafluoride at Portsmouth, Ohio and Paducah, Kentucky, and others. These nuclear chemical facilities combine the hazards of radioactive materials with those of complex chemical operations; but presently use an approach to safety management that is rooted in nuclear hazards analysis techniques. This approach tends to provide adequate coverage of the hazards associated with the radioactive materials, but does not capture the same level of detail for chemical hazards, which, in some cases, could act as the primary risk drivers for the facility.

At present, the nuclear industry and chemical industry each have their own approach to safety management. In a nuclear chemical facility, these two industries can be viewed as intersecting, and thus integrated safety measures to help ensure safe and efficient plant operations would be desirable. However, the inconsistency between the approaches of the two industries can pose a challenge for nuclear chemical facilities, which have many of the operational characteristics of a chemical plant but also must contend with radioactivity and other nuclear materials hazards (e.g. nuclear criticality). To date, the approaches of the industries are disparate.

The overall goal of this research was to analyze accidents from the chemical industry (through the chemical industry accident reports) and DOE nuclear chemical facilities (a select group of

DOE occurrence reports) for trends to develop a set of predictive or leading safety and performance measures applicable to nuclear chemical facilities; essentially, to use information from past events to derive a set of performance measures that can be used proactively to improve safety management in such facilities.

This research mined the large database available in 60 published chemical industry accident reports and safety bulletins completed by the CSB, and relevant DOE occurrence reports over the past 15 years, representing accidents that have risen to reportable thresholds during that timeframe, as well as NRC abnormal occurrences reported to Congress during the same time frame. Analyzing the information presented in the accident reports through content analysis led to a list of issues common across many accidents that were used as focus areas for performance measure development. Each issue was used as the basis for the development of a theory about safety and efficiency of operations at nuclear chemical facilities, in a process of grounded theory development. Once the issues were translated into theories, these theories were combined with the data itself, including the issue and the textual associations of related issues, to postulate a set of recommended safety and performance measures. The inspiration for these performance measures came either from literature on leading performance measures referenced in the text, or the data itself.

Once a set of potential performance measures was developed, subject matter elicitation was used to determine which performance measures were both practical and effective for implementation at a nuclear chemical facility. The first step in the subject matter elicitation was review of the proposed measures by several experts at a DOE site to eliminate any repetitive or impractical measures (i.e. no measurement possible given the current operations of a nuclear chemical facility). These experts reduced the list by more than half, leaving 17 potential performance measures for the second step, analytic hierarchy process. In the analytic hierarchy process, nuclear safety, operations, and engineering subject matter experts, 40 in total, went through a hierarchical ranking process to select those performance measures that were most impactful to nuclear chemical facility operations. After these subject matter expert elicitations, the following list of performance measures remained, where the bolded measures are those considered most impactful.

- Engineering Controls:
    - **Pertinent subject matter expert involvement in process design and/or review changes**
    - **Percentage of operators and technical staff who are able to identify controls and believe that they understand their operation**
    - Amount of time in between inspections or tests of safety systems
    - **Number of nuisance alarms or false alarms vs. number of valid alarms**
- Operating Procedures
    - Percentage of procedures reviewed for content in a year
    - **Number of operators or maintenance technicians who believe that procedures are current, accurate, and effective (by survey)**
    - **Pertinent SMEs involved in drafting procedures**
- Maintenance
    - Percentage of all safety systems and safety controls planned maintenance accomplished
    - Number of past due maintenance requests as a percentage of total maintenance requests
    - **Amount of time the plant is in operation with any safety system in an inoperable or degraded condition**

- Hazards Analysis
    - Percentage of operators and/or maintenance techs who have formal training on the Documented Safety Analysis (DSA)
    - **Pertinent subject matter expert involvement in the DSA development and maintenance**
    - Number of operations and maintenance personnel involved in DSA development and maintenance
    - **Number of past due safety action items vs. total number of safety action items stemming from previous occurrences**
- Emergency Planning
    - Number of local (county or city) Emergency Responders trained in facility (e.g. chemical or radiological) hazards and response
    - Number of emergency drills performed in a time period vs. number scheduled (or required)
    - Number of workers in an operating facility who believe that they can execute their responsibilities in the case of an emergency (by survey)

A quantitative method was used to further analyze the impact of the performance measures on safety at a nuclear chemical facility. The performance measures were matched up to nodes in several accident progression event trees of the probabilistic risk assessment for a nuclear chemical facility. The nodes were then modeled with a reduction in the failure or error probability based on guidance from the PRA data source described in the chapter. This study provided a quantitative measure of the potential impact of the performance measures at a nuclear chemical facility, through the percentage reduction in the overall event probability. The maintenance, operating procedures, and engineering controls performance measures were the most impactful to the selected events.

Finally, guidance was provided for the 17 performance measures to assist in implementing the performance measures at a facility. This guidance included a discussion about data collection including additional setup requirements (such as additional training or documentation). Guidance was also provided to assist in setting a baseline for each of the performance measures. The next phase of this process will involve piloting the performance measures at nuclear chemical facilities. These leading, integrated safety and performance measures for nuclear chemical operations will provide warning in advance of an event of degraded safety conditions, and in doing so help ensure safe and efficient operations at these facilities.

CHAPTER 1

INTRODUCTION

1.1. Overview

Regardless of the industry of origin of hazardous chemicals, a lack of proper control can result in an accident with serious consequences to workers, the environment and the public. Maintaining worker and public safety, along with protecting the environment, is a key priority in the chemical industry. Even prior to the advent of groups such as the Occupational Safety and Health Administration (OSHA) and industry groups such as the Center for Chemical Process Safety (CCPS), unexpected releases of toxic, reactive or flammable liquids were reported, yet remained a recurring problem. The introduction of OSHA's Process Safety Management (PSM) Guidelines played a large role in helping to lower the incidence of unexpected releases and other accidents at chemical facilities (U.S. Federal Record, 2013). Meanwhile, industry groups, such as the CCPS and others, have also focused on improving safety internally, by sharing lessons learned from accidents and promoting safety management. Due to this focus on safety, the chemical industry is relatively safe compared to other high hazard industries, considering the materials handled by these facilities on a daily basis (U.S. Department of Labor Bureau of Labor Statistics, 2013).

However, the overall relative safety of the chemical industry does not preclude the occurrence of accidents. Review of the recent accident records reveals that there have been accidents in the chemical industry ranging from combustible dust explosions, plant explosions and fires to chemical releases and asphyxiation. The chemical industry accident report database used in this analysis contains 60 accident reports issued between 1998 and 2012. These accidents represent 120 fatalities and 895 injuries, including chemical workers, first responders, and the public at large. At first glance, 60 accidents in 14 years may appear to be an acceptable rate (about 4 per year in a $769 billion industry in the U.S.); however, not all accidents involving injury are investigated by external groups and, consistent with the concept of continuous improvement, this research attempted to derive new insights from looking at this group of accidents as a whole.

Studying accidents to determine their causes is fairly common in high hazard industries. There are several accident databases available for study, with varying degrees of information available. Studies have shown that analyzing these accidents and applying lessons learned from them helps to avoid future accidents and reduce risk (Meal et al, 2007). The Environmental Protection Agency has a Risk Management Program that requires each facility under their purview submit a five-year accident history when they submit a Risk Management Plan (Kleindorfer et al, 2003). This database has been studied to find trends in the accidents at these facilities, including plant demographics, chemical inventories, and others (Kleindorfer et al, 2003). Some studies, such as Kahn and Abbasi, used several accident databases, worldwide to analyze the common causes which led to accidents at fixed chemical facilities (Kahn, F. and S.A. Abbasi, 1999). Kahn and Abbasi performed a statistical survey of a selection of chemical industry accidents over a 70 year period (1928 – 1997); as part of that analysis they assessed what they called ‘major factors’ that led to accidents at fixed chemical installations, such as those reviewed by the United States Chemical Safety and Hazard Investigation Board (CSB).

The history of workplace safety has demonstrated a longstanding confrontation between productivity, profitability, and process and worker safety. For the most part, the historical practice had been to eschew process safety and the safety of workers in order to make gains in productivity and increase profitability, which arguably contributed to the creation of an organizational culture in which “productivity over safety” was the predominant mentality. However, focus on several high consequence incidents -- across many industries-- such as Bhopal, Challenger, Chernobyl, and more recently, the oil and gas industry’s BP Texas City Refinery Explosion, NASA’s Columbia Shuttle Disaster, and the nuclear industry’s Fukushima Daiichi, among others, has increased the focus on worker safety. This focus has led to an increased body of work dedicated to reducing worker risk in many industries.

The nuclear industry in the United States has a safety record that demonstrates relative success over other high hazard industries. The DART rate for the Department of Energy in 2013 was 0.44, and the TRC was 0.95 (CAIRS, 2013), compared to 1.1 and 2.0 for chemical manufacturing (Department of Labor Bureau of Labor Statistics, 2013). However, the favorable safety statistics do not preclude occurrences at DOE facilities; in the same year, 1,105 occurrences were reported to the DOE from the sites (all DOE facilities) (ORPS, 2013). There is a wealth of information available for study from incidents in the nuclear and chemical industries. The 1,105 DOE occurrence reports are summaries of incidents, representative of the typical operations at nuclear chemical facilities. In contrast, the CSB produces accident reports for the most severe chemical industry accidents. The cost associated with the accident statistics described on page 1, combined with the increased focus on worker safety, has provided a partial motivation for this study, which is an evaluation of safety and health data, with an emphasis on developing performance measures for nuclear chemical facilities, using quantitative and semi-quantitative methods.

1.2. Nuclear Chemical Facilities

The Department of Energy (DOE) has been expanding the number of nuclear facilities using chemical processes to complete its waste management mission over the last decade. Recent new facilities include the Actinide Removal Process/Modular Caustic Side-solvent extraction Unit (ARP/MCU) at Savannah River, the processing plants for the deconversion of depleted uranium hexafluoride at Portsmouth, Ohio and Paducah, Kentucky, the Integrated Waste Treatment Unit (IWTU) in Idaho, and others. These nuclear chemical facilities combine the hazards of radioactive materials with those of complex chemical operations; looking more closely at the ARP/MCU process for instance, the process flow sheet is more similar to a complex chemical operation than a nuclear reactor facility. The ARP uses adsorption of Sr-90, actinides and sludge solids onto MonoSodium Titanate and filtration through a cross-flow filter to decontaminate a low-curie salt solution. The MCU process involves caustic side-solvent extraction, in which a solvent is contacted counter-currently with the salt solution in centrifugal contactors to remove cesium and recycled using a second set of contactors and wash.

The current approach to safety management at nuclear chemical facilities is rooted in nuclear hazards analysis techniques and tends to provide adequate coverage of the hazards associated with the radioactive materials, but does not capture the same level of detail for chemical hazards, which, in some cases, could act as the primary risk drivers for the facility.

At present, the nuclear industry and chemical industry each have their own approach to safety management. The current framework for eliciting feedback provided by incident reporting, evaluation and analysis at DOE nuclear facilities is one in which the DOE utilizes a systematic, detailed occurrence analysis categorization process (documented in DOE Order 232.2, *Occurrence Reporting and Processing of Operations Information* and DOE Standard 1197-2011, *Occurrence Reporting Causal Analysis*); the categorization process was informed by the practices of the commercial nuclear power industry and the Institute for Nuclear Power Operations (INPO). This process involves the implementation of a formal Causal Analysis Tree (CAT) with predesigned headings to an accident. Each category is numbered and documented for ease of incident analysis.

The main objectives of DOE O 232.2 are to keep the DOE and National Nuclear Security Administration (NNSA) informed about events that could cause potential negative effects to the health and safety of the public, the workers, the environment, DOE missions, or DOE credibility. It also serves to ensure that DOE uses organizational learning to enhance mission safety and share effective practices in order to continuously improve process safety and manage process changes (DOE, 2011c).

Reporting under Order 232.2 is required for any occurrence that results from an activity performed by facility personnel; such occurrences must be reported by facility personnel in a timely fashion and investigated and analyzed by facility management as described in the Occurrence Reporting Model, using the cause codes provided in the CAT. This DOE approach to occurrence reporting and categorization is used to write the DOE occurrence reports that have been studied in this dissertation.

The chemical industry, on the other hand, combines the general regulations and guidance of the Occupational Health and Safety Administration (OSHA), proactive industry programs initiated by various industry groups (such as AIChE [CCPS], ASME and others) and individual companies, and detailed investigations and safety bulletins released by the United States Chemical Safety Board (CSB). The CSB is an independent federal agency charged with investigation of industrial chemical incidents; the reports of this agency formed the database of chemical industry accident reports used in this analysis. The CSB performs investigations of chemical accidents at fixed industrial facilities[1] and uses informal causal analysis to identify "Key Issues" in each incident. The investigations are published as written reports. The CSB also issues recommendations to enhance safety in the chemical industry and monitors the adoption of these recommendations.

In a nuclear chemical facility, these two industries can be viewed as intersecting, and thus integrated safety measures to help ensure safe and efficient plant operations would be desirable. However, the inconsistency between the approaches of the two industries can pose a challenge for nuclear chemical facilities, which have many of the operational characteristics of a chemical plant but also must contend with radioactivity and other nuclear materials hazards (e.g. nuclear criticality). To date, the approaches of the industries are disparate.

[1] The CSB defines the scope of their accidents as those which result from the production, processing, handling or storage of a chemical substance which result in a death, serious injury, or substantial property damage at fixed industrial facilities. The definition of a fixed industrial facility is a permanent or semi-permanent facility on a fixed location; this distinction is made to clarify that the NTSB has jurisdiction over any transportation related accidents.

1.3. Motivation

The overall goal of this research was to analyze accidents from the chemical industry (through the chemical industry accident reports) and DOE nuclear chemical facilities (a select group of DOE occurrence reports) for trends to develop a set of predictive or leading safety and performance measures applicable to nuclear chemical facilities; essentially, to use information from past events to derive a set of performance measures that can be used proactively to improve safety management in such facilities. This research mined the large database available in 60 published chemical industry accident reports and safety bulletins completed by the CSB, and relevant DOE occurrence reports over the past 15 years, representing accidents that have risen to reportable thresholds during that timeframe, as well as NRC abnormal occurrences reported to Congress during the same time frame. Analyzing the information presented in the chemical industry accident reports through these varied lenses (i.e., OSHA PSM) led to the development of a series of theories about process safety at nuclear chemical facilities, and ultimately to the development of set of recommended safety and performance measures.

These safety and performance measures were reviewed by subject matter experts to ensure that they were both practical—could be implemented at a nuclear chemical facility, and effective—their implementation would provide useful information about the safety and operational status of the facility. Practical and effective integrated safety and performance measures for nuclear chemical operations will assist in monitoring the safety of facility operations, providing feedback before an accident or occurrence, and thus, help ensure safe and efficient operations.

1.4. Overview of Performance Measures

The use of performance measures to track the safety and efficiency of operations at facilities is not a new idea in either the chemical or the nuclear industry. There are two types of indicators used by these industries: leading and lagging.

Lagging indicators are the most commonly used performance measures. These are metrics based on incidents that meet the threshold for reporting by the industry, or based on the actuation of abnormal operating conditions-- they are retrospective. Lagging indicators could be determined through a causal analysis of an incident, or a review of a certain system (i.e. the number of times an alarm system has been actuated). Lagging indicators illustrate trends that may be ongoing that are contributing to multiple incidents at a facility or industry-wide. This type of indicator is useful in that it allows for the collection and dissemination of lessons learned from previous incidents, with the thought that it may prevent the same incident from occurring again, or at another facility.

Leading indicators, on the other hand, could provide an alert to degraded conditions at the facility before an incident occurs, or an abnormal operating condition is reached. However, these are also the more difficult set to determine, and the set of practical and efficient leading indicators is small and can be facility-specific. A good safety management program will include both leading and lagging indicators to ensure safe and efficient operation of the facility.

The chemical industry Center for Chemical Process Safety has spearheaded this effort for the chemical industry with the development of a set of recommended leading and lagging indicators in their publication *Process Safety Leading and Lagging Metrics – You Don't Improve What You Don't Measure* (CCPS, 2011). CCPS states that in order to "continuously improve upon process safety performance, it is essential that companies in the chemical and petroleum industries implement effective leading and lagging process safety metrics (CCPS, 2011)." The CCPS also provides examples of lagging and leading metrics for the chemical industry in the guide, which have been used to help develop metrics recommended by this dissertation.

1.5. Structure of the Dissertation

The work presented in this dissertation represents a semi-quantitative analysis of accidents from the chemical industry and incidents from nuclear chemical facilities in the U.S., and the development of theories to improve safety and efficiency of operations at nuclear chemical facilities, as well as potential performance measures that could be used as leading indicators of the status and health of safety structures and programs at the facility.

In Chapter 2, an overview of the current status of safety programs in the nuclear industry and chemical industry sets the backdrop for the study. The regulations and standards for process safety differ between the nuclear industry and the chemical industry, and enforcement of these regulations also differs. An overview of these standards and their enforcement is rounded out with a review of existing regulations relevant to nuclear chemical facilities, where they exist.

This analysis is complemented by a review of existing literature about safety in these industries, and how it differs, as well as literature about nuclear chemical facilities.

In Chapter 3, the stage is set for studying accidents to develop performance measures. While accident analysis is typically used to track lagging indicators, its use in this study is to develop leading indicators. The methodology and rationale behind this unique study is described including the various methodologies used during the analysis: content analysis, development of grounded theory, analytic hierarchy process, and probabilistic risk assessment. The case is also made for content analysis, as opposed to the traditional use of root cause analysis.

Chapter 4 provides the results of the analysis of chemical industry accidents. In this chapter, an overview of the chemical industry database leads into a discussion of the two distinct reviews of chemical industry accidents performed for this study, the Key Issues analysis, and the content analysis. The results from both reviews are presented and compared, providing the full picture of the studied accidents in the chemical industry.

Chapter 5 contains the results of the analysis of nuclear chemical facilities accidents and includes information on the occurrences used from the DOE's Occurrence Reporting and Processing System as well as the NRC's Abnormal Occurrence Reports to Congress. Trends from the ORPS reports as well content analyses of both ORPS and NRC reports are included in this chapter and compared to the results from the chemical industry.

In Chapter 6, the development of the performance metrics is described, from reported data in Chapters 4 and 5 to theories for improving safety and efficiency of operations, to performance metrics recommended for nuclear chemical facilities. This chapter also contains the results of an expert review of the proposed performance metrics, weeding out those that were not considered practical or effective -- leaving a manageable set to be recommended to nuclear chemical facilities.

Then performance measures were applied to a nuclear chemical facility, the Defense Waste Processing Facility, in Chapter 7, to test their impact represented by their quantitative reduction in risk at that facility, and what effects they might have on safety and efficiency of operations. Also in Chapter 7, the application of these metrics to nuclear chemical facilities is discussed in detail, with recommendations and caveats from interviews with subject matter experts. Chapter 8 offers ideas for future work and provides a summary of the findings of this dissertation.

1.6. Abbreviated Results

This dissertation illustrated the use of qualitative and quantitative data from accidents in the chemical industry and at nuclear chemical facilities to develop theories and subsequent performance measures to improve safety and efficiency of operations at nuclear chemical facilities.

The results from the dissertation showed that these performance measures had a positive impact on safety at nuclear chemical facilities. Review by safety and operations subject matter experts using a survey illustrated that the performance measures above were both practical and effective for measuring the safety and health of a nuclear chemical facility. Further, the performance measures were applied to a probabilistic risk assessment and demonstrated a measurable reduction in the overall probability of three studied accidents. Finally, guidance was developed for implementing these performance measures at a nuclear chemical facility, making quantifiable metrics to determine degraded or degrading safety conditions.

CHAPTER 2

BACKGROUND AND LITERATURE SURVEY

2.1. Introduction

This work necessitated a literature and background survey of the current status of safety in the chemical industry and nuclear industry, both domestic and international. The goal of Chapter 2 is to provide an overview of this literature study, describing the most relevant and useful pieces of information to this work. The objectives of this chapter are to describe the current status of safety in the nuclear industry, the current status of safety at nuclear chemical facilities, the current status of safety in the chemical industry, and to provide an overview of the U.S. Chemical Safety and Hazard Investigation Board.

The literature survey conducted involves several categories of studies spread out over three distinct topics: safety in the nuclear industry, safety in the chemical industry and work that "bridges the gap" for safety in nuclear chemical operations. In the literature review for each of these sections, there are several sets of resources. In completing the review, special attention was paid to gathering industry standards and practices, as well as safety research from peer-reviewed journals and government reports.

One of the distinct sets of documents that form the literature survey is the set of regulations that govern each industry. For safety in the nuclear industry, these are largely DOE and Nuclear Regulatory Commission (NRC) regulations, with some additional guidance provided at times by the Environmental Protection Agency (EPA) and OSHA. In the chemical industry, these regulations include OSHA regulations and standards as well as some EPA standards, along with recommendations from the CSB. For several of the more heavily documented regulations, there are also guidance documents, which detail more clearly the processes for adhering to the regulation.

These are supplemented by government reports and audits detailing successes and shortcomings in safety, and agencies implementing safety practices, such as the EPA Inspector General's audits of the CSB (e.g. EPA, 2013). These reports shed light on the efficacy of existing policy and guidance in both industries as well as provide insight into incidents and shortfalls. Also in the DOE nuclear industry, there are recommendations from the Defense Nuclear Facilities Safety Board (DNFSB) which provide a basis for revised practices such as safety management and culture improvements in the defense nuclear facilities of the DOE (DNFSB, 1995; DNFSB, 2011). The commercial nuclear industry also has guidelines from INPO, however, for this analysis, the focus is on DOE nuclear, not commercial, facilities, as DOE is the primary owner of nuclear chemical facilities.

A second set of documents that compose the literature survey are peer-reviewed journal articles relating to safety in the nuclear and chemical industries. In the chemical industry, this includes several articles on: trends and concerns in chemical safety, achieving stronger chemical safety, knowledge management and organizational learning, hazard evaluations and worker safety, among others. In the nuclear industry, the same topics as those in the chemical industry accident reports are covered, with the addition of some specific events and lessons learned at nuclear facilities. Interestingly, several of the articles relating specifically to the nuclear industry address a perceived lack of coverage in fuel cycle facilities for chemical hazards[2].

The final classification of research in the literature survey includes interviews with experts in the field of nuclear safety and chemical safety. These interviews are particularly helpful in uncovering new potential sources and understanding the complexity of the regulatory process. They also provide the experience and feedback necessary to better understand the nuances of safety at nuclear and chemical facilities.

2.2. Safety in the Nuclear Industry

The following sections describe the current status of safety in various groups of the nuclear industry including the Department of Energy, the Nuclear Regulatory Commission, and the International Atomic Energy Agency.

2.2.1. Department of Energy Nuclear Facilities Safety

One approach to managing risk in the nuclear industry is described as "operation as experimentation." According to Perin, high-hazard industries have two contrary theories of risk: (1) organizational and technological complexities create blind spots that make the organization vulnerable to accidents, as any high-hazard operation produces risks through operation; and (2) high-hazard systems are demonstrably capable of high reliability with strict adherence to operating rules and procedures (Perin, 1998, Page 104). In particular, Perin stresses that while

[2] Laul et. al., (2006), and Cournoyer et. al., (2013) among others.

control paradigms have limited the number of significant events, in some cases, they were ineffective at preventing accidents or mitigating their severity. Thus, rather than working solely from a pre-accident risk mitigation plan, she suggests using knowledge gained from accidents to find root causes and potential sources of error and transmit the results to future nuclear facilities with the hope of mitigating future risk (Perin, 1998, Page 107).

The DNFSB made a recommendation to the DOE in 1995 that the DOE commit to upgrading its nuclear safety program to improve the integration of safety into work planning and performance (DNFSB Recommendation 95-2, *Integrated Safety Management* (ISM) (DNFSB, 1995, Page 54066)). The main objective of this recommendation was to ensure that the operational controls for hazardous work and other operational commitments, identified through hazard analysis and related work-planning activities, are reflected in operational procedures and that operating personnel are trained and qualified to perform accordingly (DNFSB, 1997, Page 1-1). The DNFSB subdivides this work into three underlying concepts that are required for an organization to benefit from a formality of operations plan: safety culture, defense in depth and a framework of controls (DNFSB, 1997, Page 3-1). In this analysis, the focus of DOE related safety is Integrated Safety Management, and in particular, its application to DOE Office of Environmental Management (EM)[3].

EM owns the preponderance of nuclear chemical facilities in the DOE and has implemented DNFSB Recommendation 95-2 in its approach for ensuring that the public, workers, and

[3] The focus of this literature review is the application of ISM to DOE EM, a simplification to the discussion as this is one particular application of ISM to a DOE Organization. However, this research and the results and conclusions are intended to provide safety and performance measures that are potentially applicable to all DOE nuclear chemical facilities.

environment are protected. EM also uses the term Integrated Safety Management (DOE ISM). All EM sites are required to adhere to two safety expectations for any work performed therein: (1) safety is the dominant characteristic and value of EM and (2) safety drives the business methodology for EM[4]. Safety culture within EM is founded on several values such as demonstrating a commitment to safety through decision-making and leaders' actions, creating an environment in which each employee feels responsible for safety and embracing organizational learning, among others. EM believes that all accidents are preventable and an accident-free workplace can be achieved through careful planning, close attention to hazard controls, worker involvement in task planning, and stopping work where outcomes are uncertain[5].

A primary focus of DOE ISM is to prevent accidents from occurring in the first place. EM[6] has found that this can be achieved through several Guiding Principles: (1) line management responsibility for safety, (2) clear roles and responsibilities, (3) competence commensurate with responsibilities, (4) balanced priorities, (5) identification of safety standards and requirements, (6) hazard controls tailored to the work being performed and (7) clear operations authorization of work prior to commencement (DOE, 2011a). In order to monitor occurrences at defense nuclear facilities, DOE ISM has a set of safety performance indicators that are maintained on a daily basis and summarized monthly. These include OSHA statistics such as: significant injuries, near misses, total recordable cases rate, days away restricted on job transfer case rate (DOE, 2008, Pages 7-8). In addition, DOE monitors incidents in the following categories: occupational safety/industrial hygiene, fire protection, electrical safety, authorization basis, nuclear criticality,

[4] The EM Program Management Portion of the DOE webpage. Found at http://energy.gov/em/services/program-management/safety accessed May 2013.
[5] This sentiment is expressed in the DOE Integrated Safety Management System Guide and can be found on DOE EM's safety web page at http://energy.gov/em/services/program-management/safety. (Accessed September 2013).
[6] As well as NNSA and all DOE defense nuclear facilities.

radiological control, conduct of operations, equipment degradation or failure, and environmental releases (DOE, 2008, Page 8). DOE-EM also performs analyses on these categories periodically to identify incident trends for organizational learning (DOE, 2008, Page 8). As indicated in several conversations documented with a DOE- EM safety manager, a number of these performance indicators would also be of importance in the chemical industry and are of consequence in either type of facility, or as in the case of the proposed research, a nuclear chemical facility (Hutton, 2012).

While the DOE's ISM process, and several of the others discussed above, are focused on preventing accidents from occurring, if there is an occurrence[7], the DOE turns to the accident investigation process described in DOE Order 225.1B and the subsequent causal analysis (through Order 232.2) to identify lessons to be learned (DOE, 2011e; DOE, 2011c).

DOE Order 225.1B defines the process for accident investigation of DOE occurrences through the following steps: (1) determination of whether or not an accident is of the severity to warrant the appointment of an Accident Investigation Board (AIB), (2) notification of other agencies in accordance with public laws or regulations, (3) conducting the investigation, to be described in further detail below, and (4) closing out the investigation (DOE, 2011e, Pages 3-8). The first step in the investigation process is to evaluate the severity of an accident and appoint the AIB, which consists of a chairperson and 5-6 members, all DOE Federal employees with subject matter expertise and knowledge of DOE's ISM program. During the investigation process, the AIB will

[7] An occurrence is defined by DOE O 232.2 as follows: One or more (i.e., recurring) events or conditions that adversely affect, or may adversely affect, DOE (including NNSA) or contractor personnel, the public, property, the environment, or the DOE mission. Events or conditions meeting the criteria thresholds identified in this Order or determined to be recurring through performance analysis are occurrences. An accident is a high consequence occurrence, and the DOE has few occurrences in the ORPS that would be considered accidents.

examine the accident scene, investigate interested and/or impacted individuals, organizations, management systems or facilities, examine DOE and contractor documentation, interview witnesses or personnel associated with the accident and perform engineering tests and analyses as appropriate. From these data sources, the AIB will derive causal factors (direct, root and contributing causes) associated with human performance and safety management systems which will be used to support the development of an accident investigation report. In closing out the investigation, Lessons Learned will be formally distributed, and corrective actions must be approved, completed and implemented (DOE, 2011e, Pages 5-8). Only the most impactful accidents are assessed using the DOE O 225.1B process. DOE Order 232.2 defines the DOE method for occurrence reporting and processing of operations information. Essentially, this order lays out the mechanisms and methodologies that DOE sites are required to use when reporting and analyzing occurrences. It additionally designates how and under what circumstances an occurrence must be reported. In this context, "occurrence" is a DOE term of art encompassing ten major groups of events at facilities: operational emergencies; personnel safety and health accidents and illnesses; nuclear safety basis violations; facility status degradations; environmental releases; exceeding radioactive contamination/radiation control limits; nuclear explosive safety process issues; packaging and transportation anomalies; noncompliance with Environmental Safety and Health (ES&H) notifications; and a "catch-all" category of management concerns/issues. Occurrence reports thus represent a category of off-normal events that are important for the purpose of continuous improvement but do not rise to the level of impact warranting a DOE O 225.1B accident investigation.

These major event categories are further segmented into subgroups. For example, the major category "Personnel Safety and Health," is further divided into six subgroups: A) Occupational Injuries, B) Occupational Exposure, C) Fires, D) Explosions, E) Hazardous Electrical Energy Control, and F) Hazardous Energy Control (other than electrical). Within each subgroup, the Order sets forth criteria for categorizing occurrences within the scheme according to the "severity" of the occurrence as rated according to significance categories.

These significance categories "provide a means to reflect perceived risk associated with a given occurrence… [and] take into consideration the potential consequence of an occurrence in terms of health, safety and security to personnel, the public, the environment, and the operational mission (DOE, 2011(c), Attachment 2 Page 1)." Significance categories decrease in severity from Operational Emergency to Significance Categories 1 through 4 (with the additional Category R reserved for recurring occurrences).

Under the order, Operational Emergency (OE) and Significance Category 1 (SC1) occurrences "reflect management's judgment that circumstances pose an immediate or near term potential for harm unless promptly mitigated or that the occurrence meets reporting thresholds established by other regulatory requirements." An OE is defined as "major unplanned or abnormal events or conditions that: involve or affect DOE/NNSA facilities and activities by causing, or having the potential to cause, serious health and safety or environmental impacts; require resources from outside the immediate/affected area or local event scene to supplement the initial response; and, require time-urgent notifications to initiate response activities at locations beyond the event scene. SC1 categorization is reserved for those occurrences that are severe, yet do not fall within the bounds of the OE definition. Less severe occurrences (SC2-SC4; SCR) still require mitigation, response and reporting, but do not necessitate the sort of emergency response necessitated by an OE/SC1 occurrence.

In addition to laying out a categorization scheme, DOE Order 232.2 also sets forth occurrence report preparation guidelines that explain the required contents and details for each report. Finally, the Order includes an occurrence-reporting process that explains the timeline governing when notifications and reports must be provided, and to whom those reporting notifications and reports must be sent.

DOE Standard 1197-2011, *Occurrence Reporting and Causal Analysis* describes a component of the occurrence reporting requirements set forth by DOE Order 232.2: causal analysis. As part of the occurrence reporting required by DOE Order 232.2, an occurrence report must contain a causal analysis: "apparent causes and causal factors, which include direct, root and contributing causes, should be identified as a result of these analyses." The Standard contains a Causal Analysis Tree (CAT), see below, to be used to determine the appropriate cause codes applicable to an occurrence. The CAT consists of 7 main branches that divide possible causes for an occurrence as follows: Design/Engineering Problem (A1), Equipment/Material Problem (A2), Human Performance Less Than Adequate (LTA[8]) (A3), Management Problem (A4), Communication LTA (A5), Training Deficiency (A6), and Other Problem (A7).

[8] LTA is a term applied to indicate less than adequate performance, or weakness in a given area. In DOE STD 1197 this acronym is used to define breakdowns or gaps in a safety function.

In addition to DOE investigations of individual accidents at DOE facilities, the Defense Nuclear Facilities Safety Board (DNFSB) conducts investigations of individual accidents, or broader safety issues or concerns across the DOE complex, which may have adversely affected public health or safety (U.S.C. Ch. 42 No. 2286, 1989, Page 3). From these independent investigations, the DNFSB can issue recommendations, which must be addressed by the DOE through a formal response and implementation plan. Implementation progress is tracked by the DNFSB.

2.2.2. Safety at NRC Nuclear Facilities

The NRC regulates safety at commercial nuclear fuel cycle facilities (gaseous diffusion plants, highly enriched uranium fuel fabrication facilities, low-enriched uranium fuel fabrication facilities, and uranium hexafluoride production facilities) in the U.S. using a series of inspections focused on reviews of safety, safeguards, and environmental protection, as well as reporting on abnormal occurrences at NRC licensed facilities. These inspections, which may occur multiple times in a year, cover activities such as nuclear criticality control, chemical process, emergency preparedness, fire safety, and radiation safety (NRC, 2014). The NRC may also enforce compliance to regulations using sanctions called enforcement actions which may take the form of notices, fines, or restriction/removal of operating licenses. Presently, the NRC is working to enhance oversight of fuel cycle facilities by developing a structured regulatory framework, the Revised Fuel Cycle Oversight Process (RFCOP) (NRC, 2015). The NRC purview over nuclear fuel cycle facilities is established in 10 CFR 70, which establishes the procedures and criteria for NRC issuance of licenses to receive title to, own, acquire, deliver, receive, possess, use, and transfer special nuclear material; and establishes and the terms and conditions upon which the

Commission will issue such licenses (CFR, 1991b), and 10 CFR 40, which establishes the procedures and criteria for source and byproduct materials licensing (CFR, 1991a).

Abnormal occurrences are defined by Public Law 93-438 as an unscheduled incident or event that the U.S. Nuclear Regulatory Commission (NRC) determines to be significant from the standpoint of public health or safety (U.S. Public Law, 1974). These abnormal occurrences are reported to Congress annually by the NRC. The NRC considers an event to be an abnormal occurrence if it involves a "major reduction in the degree of protection of public health or safety" and could include: "moderate exposure to, or release of, radioactive material licensed by or otherwise regulated by the Commission; major degradation of essential safety-related equipment; and major deficiencies in design, construction, use of, or management controls for facilities or radioactive material licensed by or otherwise regulated by the Commission (NRC, 2014b, Appendix A)."

Aside from abnormal occurrences, the NRC has technical specifications to review the required Safety Analysis Report provided by the facility during the licensing process. These specifications are facility specific; for example, the Light Water Reactor safety analysis must include review of the site characteristics, design of the structures, components, equipment and systems, engineered safety features, conduct of operations, accident analysis, and severe accidents, among other topics (NRC, 2014c).

2.2.3. Safety Guidance from International Atomic Energy Agency Nuclear Facilities

The International Atomic Energy Agency (IAEA) publishes a set of international safety standards that provide guidance that can be applied to facilities in the U.S. According to the IAEA, these international safety standards "provide support for States in meeting their obligations under general principles of international law, such as those relating to environmental protection and promote and assure confidence in safety (IAEA, 2009, Page vii)." These standards "establish fundamental safety principles, requirements and measures to control the radiation exposure of people and the release of radioactive material to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur (IAEA, 2009, Page viii)." Such safety standards and subsequent guides exist for a wide array of safety topics including radiation protection, radioactive waste management, maintenance, surveillance, training, commissioning, among many others.

Similar to the DOE's ISM, IAEA Safety Requirement GS-R-3, The Management System for Facilities and Activities provides the requirements for a management system that integrates safety, health, environmental, security, quality, and economic elements with safety being the fundamental principle. The requirement states that process requirements, such as applicable regulatory, statutory, legal, safety, health, environmental, security, quality and economic requirements, are specified and addressed, and hazards and risks are identified, together with any necessary mitigatory actions (IAEA, 2006, Page 11).

The IAEA staff also investigates international accidents and produces reports to distribute lessons learned to an international audience. These reports may take the form of short accident overviews with and overview and lessons learned, or longer accident reports with a synopsis of accidents and recommendations, as well as lessons learned. The main goal of these investigations is to disseminate information about the accidents to potentially prevent future recurrence at similar facilities. For example, the IAEA developed a special report to cover a radiological accident that occurred in 1993 at the reprocessing plant at Tomsk, Russia (IAEA, 1998). The recommendations of this investigation included similar themes to those discussed in this research including a recommendation that plant managers “ensure that operational procedures are continually appraised, equipment is updated and personnel adequately trained for the type of work involved;” and to “check continuously the equipment at their disposal for monitoring the effects of their operations and ensure that it is suitable for both normal and emergency situations (IAEA, 1998, Pages 72-73)”. The IAEA may also determine the necessity of a topic-specific meeting based on an accident type or theme to provide more general lessons learned to the industry.

2.3. Safety at Nuclear Chemical Facilities

The following sections describe the current status of safety at nuclear chemical facilities, where information is available, including the Department of Energy, Nuclear Regulatory Commission, International Atomic Energy Agency, and safety culture.

2.3.1. DOE Nuclear Chemical Facilities

Chemical safety at DOE facilities is guided by two handbooks. DOE HDBK 1101-2004, *Process Safety Management for Highly Hazardous Chemicals* provides the information required to determine if a chemical process is covered by OSHA's Process Safety Management (PSM) rule and gives an interpretation of the PSM rule, describing DOE programs that may satisfy the requirements of the rule (DOE, 2004a). DOE HDBK 1100-2004 *Chemical Process Hazard Analysis* facilitates the performance of process hazard analyses (required under PSM) at DOE facilities (DOE, 2004b). Each facility must prepare a Documented Safety Analysis (DSA) in accordance with DOE-STD-3009-2014, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis*, which provides documentation of the safety basis on which the facility will operate (DOE, 2014b). The development of the DSA for nonreactor facilities is similar to that of reactor facilities and requires site characterization, identification of the scope of work and process characteristics, hazard evaluation, accident analysis, control selection, derivation of technical safety requirements and safety management programs, among other goals (DOE, 2014b).

The DOE has a Chemical Safety Program and a Chemical Safety Topical Committee (CSTC), cosponsored by the DOE Office of Worker Safety and Health Policy and the ESH Workgroup of the Energy Facility Contractors Group (EFCOG). The purpose of the Chemical Safety Program is to provide a forum for the exchange of best practices, lessons learned, and guidance in the area of chemical management. The CSTC provides a forum for DOE and DOE Contractor personnel to identify chemical safety-related issues of concern and find solutions to these issues (DOE, 2014a).

2.3.2. Safety at NRC Nuclear Chemical Facilities

Some work has been completed in the nuclear industry defining specific ways with which to deal with the chemical hazards within a nuclear facility that also contains chemical hazards. One such document is NUREG 1601, *Chemical Process Safety at Fuel Cycle Facilities* (NRC, 1997b). This report was designed to provide some broad guidance on chemical process safety issues that could arise at a fuel cycle facility and provide potential mitigation techniques for chemical incidents to decrease the potential for radiological and chemical exposure to workers, the public and the environment. NUREG 1601 lists four types of hazards that are generally associated with a fuel cycle facility: (1) radiation risk from radioactive materials, (2) chemical risks from radioactive materials, (3) plant conditions which affect the safety of radioactive materials and (4) plant conditions which result in an occupational risk. Hazards 1-3 are the responsibility of the NRC; Hazard 4 is typically the responsibility of OSHA.

There are several requirements for chemicals at an NRC regulated nuclear facility. The first requirement is the collection of chemical process information and the second, the availability of such information to the employees responsible for chemical process safety in the facility. This information should include at minimum a process description, purpose, material form, process chemicals, process variables, process control, materials of construction, safety features, and a discussion of auxiliary systems such as bulk chemicals, utilities, ventilation, traps and filters and emergency systems (NRC, 1997b). A third requirement states that a hazard audit should be performed that includes a system review to address process chemistry, the effects of variable chemical additions, energy sources, materials of construction and others (NRC, 1997b).

2.3.3. Guidance from IAEA for Nuclear Chemical Facilities

Safety Requirements NS-R-5, the Safety of Nuclear Fuel Cycle Facilities also describes the IAEA requirements for chemical safety. The requirement states that some facilities may use “large quantities of hazardous chemical substances and gases, which may be toxic, corrosive, combustible, reactive (i.e. give rise to exothermic reactions) or explosive, and consequently may give rise to the need for specific safety requirements in addition to requirements for nuclear safety (IAEA, 2008, Page 1).” Further, the requirement states that in the context of fuel cycle facilities, “the control of events initiated by chemical hazards can have a significant bearing on achieving the fundamental safety objective and events initiated by chemical hazards shall be considered in the design, commissioning and operation of the facility (IAEA, 2008, Page 4).” Guidance related to the chemical hazards is offered in several IAEA Safety Guides (e.g. IAEA, 2010), and the requirement also recommends standards from the chemical industry. NS-R-5 also requires the use codes and standards for chemical hazard protection.

For example, Specific Safety Guide No. SSG-5, Safety of Conversion Facilities and Uranium Enrichment Facilities considers some of the chemical hazards associated with conversion and enrichment facilities and discusses the importance of covering chemical hazards: Along with UF6, large quantities of hazardous chemicals such as HF are present, therefore, safety analyses for conversion facilities and enrichment facilities should also address the potential hazards resulting from these chemicals (IAEA, 2010, Page 4).” The publication then provides recommendations for the construction, commissioning, and operation of conversion and enrichment facilities with a focus on chemical hazards.

2.3.4. Safety Culture at Nuclear Chemical Facilities

Another topic that nuclear chemical facilities must contend with is safety culture, defined by the DOE as “the organization’s values and behaviors modeled by its leaders and internalized by its members, which serve to make safe performance of work the overriding priority to protect the workers, public, and the environment (DOE, 2011a, Page 6).” Several reviews of safety culture at nuclear waste processing facilities in particular illustrate the commonalities between the chemical and nuclear industries and pose several important findings that provide perspective for this research. One such analysis suggests that the three major drivers for safety culture include management engagement, effective work planning and procedures, and procedure adherence with a questioning attitude to ensure procedural problems are identified and fixed (Lowes, 2012, Page 8).

Many experts recommend the use of organizational learning and knowledge management as a way to use accident precursors and experience in high-hazard industries as a way to avoid accidents in the future. One such expert is John Carroll from the MIT Sloan School of Management. His work defines accident precursors as events that have to occur for an accident to happen but have not yet resulted in an accident (Carroll, 2004, Page 127). His research emphasizes the values of using precursor events as a test of the adequacy of the system defenses and a way to collect knowledge about events (Carroll, 2004, Page 127). In particular, his research focuses on problem investigation teams at nuclear and chemical facilities, studying how team learning, organizational learning and individual learning are connected in these environments. One of the problems he cites with these investigation teams is that the causes found are typically those that are most familiar to the analysts themselves. Typically the investigation teams see what they expect to see, rather than what might be less obvious (Carroll, 2002, Page 10). This could illustrate an inherent difficulty in incident investigation. Investigators are industry experts and may be expecting a certain outcome to the investigation; thus, there is a chance they might find what they are expecting rather than what is there. However, in the context of this research, as the CSB uses independent subject matter experts rather than industry experts working at the facility which is being investigated, the effects of this phenomenon should be minimized.

2.4. Safety in the Chemical Industry

The following sections describe the current status of safety in the chemical industry including OSHA Process Safety Management, the EPA's Risk Management Plan, the American Chemistry Council, the American Institute of Chemical Engineers, and academic chemical safety research.

2.4.1. OSHA Process Safety Management

Process Safety Management (PSM), a program of OSHA, was created in 1992 because unexpected releases of toxic, reactive or flammable liquids had been reported for years and continued to occur. Regardless of the industry of origin of these highly hazardous chemicals, a lack of proper control can result in an accident with serious consequences (OSHA, 2000, Page 1). The PSM program emphasizes the management of hazards associated with these highly hazardous chemicals and establishes a management program complete with integrated technologies, procedures and management practices.

OSHA regulations and the PSM Guidelines are frequently cited as the reason the chemical industry is comparatively safe, considering the high hazard materials handled by these facilities on a daily basis[9]. The PSM Guidelines were created to prevent unwanted releases of hazardous chemicals and prevent exposures to employees, the public or the environment. The chemical industry (through these guidelines) predicts that, similarly to the nuclear industry, the most effective PSM program requires a systematic approach of evaluating the entire chemical process (OSHA, 1994, Page 1). Important review categories for PSM include: chemical hazards, process technology and equipment, process safety information, employee involvement, process hazard analysis, operating procedures, employee training, contractor requirements and responsibilities, pre-startup safety reviews, hot work permitting, management of change, incident investigation, emergency planning and response, compliance audits, trade secrets, and mechanical integrity (OSHA, 1994, Pages 3-16).

In the aftermath of accidents such as the BP (formerly British Petroleum) Texas City refinery explosion of 2005, OSHA created a special emphasis program (SEP) on the national level, the National Emphasis Program. In the case of the BP Texas City refinery explosion, the refinery

[9] Citations include successes of OSHA's PSM cited in 78FR236 (2013), Pages 73756-73768, NEP Program highlighted by Barab (2012), Ozog et. al., (2012) among others.

National Emphasis Program was created to evaluate the implementation of existing PSM programs within the refinery industry (Ozog and Forgione, 2012, Page 27). After this pilot scale program demonstrated some level of success, OSHA rolled out a chemical National Emphasis Program to shift the focus onto any PSM covered facility[10]. During this program, OSHA found that although the PSM programs were formally in place at all covered facilities, their implementation is often either incomplete or insufficient (Ozog and Forgione, 2012, Page 27). Thus, OSHA's chemical National Emphasis Program will allow for the investigation (either planned or unplanned) of PSM at facilities to determine to what degree the plan is implemented. These investigations are to be performed in addition to the CSB investigations at the same sites. In a similar fashion to the CSB recommendations, OSHA releases action items and identifies corrective actions. However, since OSHA is the regulator, these action items must be completed for the facility to be in compliance with the required PSM guidelines. After the completion of the Chemical NEP pilot in 2011, 173 inspected sites were issued citations, with approximately 60% of the citations relating to PSM. The most frequent PSM citations were Mechanical Integrity (23%), Process Safety Information (21%) and Process Hazard Analysis (16%) (Barab, 2012, Page 3).

[10] The following is the definition of a PSM covered facility: A process which involves a chemical at or above the specified threshold quantities listed in an appendix; A process which involves a Category 1 flammable gas (as defined in 1910.1200(c)) or a flammable liquid with a flashpoint below 100 °F (37.8 °C) on site in one location, in a quantity of 10,000 pounds (4535.9 kg) or more except for: Hydrocarbon fuels used solely for workplace consumption as a fuel (e.g., propane used for comfort heating, gasoline for vehicle refueling), if such fuels are not a part of a process containing another highly hazardous chemical covered by this standard; Flammable liquids with a flashpoint below 100 °F (37.8 °C) stored in atmospheric tanks or transferred which are kept below their normal boiling point without benefit of chilling or refrigeration. OSHA. 2012.

2.4.2. EPA Risk Management Plan

The EPA also has a requirement for risk management at high hazard facilities. The Risk Management Plan (RMP) implements Section 112(r) of the 1990 Clean Air Act amendments and requires facilities that maintain an inventory above a certain threshold of particular hazardous substances (a list is maintained by the EPA) to submit and update a risk management plan to the EPA at least every 5 years. The RMP is made accessible to members of the community, and can be particularly useful to local emergency responders who may respond to emergencies and accidents at the facility.

The RMP for each facility must include: a hazard assessment that details the potential effects of an accidental release, an accident history of the last five years, and an evaluation of worst-case and alternative accidental releases; a prevention program that includes safety precautions and maintenance, monitoring, and employee training measures; and an emergency response program that spells out emergency health care, employee training measures and procedures for informing the public and response agencies (e.g. the fire department) should an accident occur (EPA, 2015).

2.4.3. American Chemistry Council Responsible Care

Along with OSHA and EPA regulations, there is industry guidance for safety at chemical facilities. The American Chemistry Council (ACC) provides such guidance for the global chemical industry to improve employee safety, and work towards improving the health of the environment as a whole through the Responsible Care Program. Established in 1984, the Responsible Care program was adopted by the U.S. in 1988, and participation is mandatory in order to be a member of the ACC. The relevant guiding principles of Responsible Care are as follows (ACC, 2015):

- To work with customers, carriers, suppliers, distributors and contractors to foster the safe and secure use, transport and disposal of chemicals and provide hazard and risk information that can be accessed and applied in their operations and products.
- To design and operate facilities in a safe, secure and environmentally sound manner.
- To instill a culture throughout all levels of the organizations to continually identify, reduce and manage process safety risks.
- To cooperate with governments at all levels and organizations in the development of effective and efficient safety, health, environmental and security laws, regulations and standards.
- To make continual progress toward a goal of no accidents, injuries or harm to human health and the environment from products and operations and openly report health, safety, environmental and security performance.

The Responsible Care Management System is a key piece of the Responsible Care program, that provides a management approach to improve company performance in the areas of community awareness and emergency response; security; distribution; employee health and safety; pollution prevention; and process and product safety. Participation in the system requires an auditor to assure there is a structure in place to measure, manage, and verify performance meeting the standards of Responsible Care.

A part of the management system, the Process Safety Code is a set of management practices that address leadership and culture, accountability; knowledge, expertise and training; understanding and prioritization or process safety risks; comprehensive process safety management system; information sharing; and monitoring and improving performance (ACC, 2012, Pages 1-2). The Process Safety Code is designed to work in concert with the other branches of the Responsible Care program, as well as OSHA’s PSM and EPA’s RMP, both discussed previously.

Responsible Care participation also requires the monitoring of performance measures including environmental metrics such as hazardous air pollutants released, SOx and NOx emissions and net water consumption; energy metrics such as greenhouse gas emissions and energy efficiency; safety metrics such as the number of process safety incidents, DOT-reportable distribution incidents, OHSA recordable lost workday incidence and fatalities; and accountability metrics such as community outreach and emergency response initiatives.

2.4.4. American Institute of Chemical Engineers Center for Chemical Process Safety

Aside from the work of OSHA, the EPA, and the ACC, there are industry groups, such as the American Institute for Chemical Engineers’ (AIChE) Center for Chemical Process Safety (CCPS), which dedicate their research to the analysis of safety in the chemical industry, both in terms of accident prevention and accident investigation. CCPS is a corporate membership organization composed of some members of AIChE that addresses process safety needs through developing guides, courses, and literature to improve industrial process safety. One area of CCPS work of particular utility to this study was the guidelines for Hazard Evaluation Procedures, which provided current hazard analysis methodologies (CCPS, 2008). CCPS also has a guide written about performance measure use which had several leading performance indicators that inspired those developed later in this study (CCPS, 2011).

2.4.5. Academic Chemical Safety Research

Chemical safety is a field which has been studied in great detail in the last several decades, largely due to the high consequences of accidents at chemical facilities such as the BP Texas City Refinery Explosion, and the Bhopal Methyl Isocyanate (MIC) release. The three main categories of safety topics in this industry have been described as: hazard identification, risk assessment and accident prevention (Kharbanda and Stallworthy, 1988, Page 3). Researchers agree that despite the highly hazardous nature of the materials used in the chemical industry, overall, it has an excellent safety record. In their book, Kharbanda and Stallworthy define five (5) major elements to safety in the chemical industry. The first is that experience is the best teacher—the best way to increase safety is to learn and apply lessons learned from accidents that have already occurred. This speaks to the importance of the investigation side of safety management in the chemical industry as a primary change maker. The second is that management is responsible for minimizing risk. This is consistent with the principle in the nuclear industry that the manager must illustrate dedication to safety management (stated in DOE ISM—line management is responsible for safety)[11]. Although in many instances, equipment failure is seen as the proximate cause of an accident, failures of safety management programs are of equal importance. The third is loss prevention. As the chemical facilities studied

[11] This study was published in 1988, and thus predates much of the nuclear industry safety culture/safety conscious work environment work, so while the issues addressed are similar to the DOE or NRC approach, the terminology differs to a degree.

were all businesses, the primary goal is to make a profit. Thus, loss prevention can also become a major motivator for safety in the chemical industry. Kharbanda and Stallworthy suggest that this loss prevention can be thought of as a combination of developments in operational and diagnostic technology, insurance, and regulatory control (Kharbanda and Stallworthy, 1988, Pages 3-38).

A study at several chemical agent destruction pilot plants contains information about the application of process safety metrics to these high-hazard facilities. For instance, several of the key causes of process safety accidents identified include standard operating procedure deficiencies, equipment malfunction, human factors and communications deficiencies (National Research Council, 2011, Page 4). These are typically thought of as lagging metrics, or after-accident metrics for safety. The study also looked at what were believed to be several leading metrics including: process safety near-miss events, closure of action items, completion of emergency response drills, management of change, and others (National Research Council, 2011, Page 4). In addition to discussing leading and lagging performance metrics, this report also emphasized the importance of managerial leadership in these facilities, citing their role in setting the tone and articulating performance expectations. The study of managerial leadership yields an important factor, highlighted in much of the literature with regards to safety at nuclear facilities: safety culture. The safety culture is a way in which safety is managed in the workplace, which focuses on the attitudes, beliefs, perceptions and values that are embodied by the employees during their tenure.

Other studies of incidents in the chemical industry work to illustrate how accidents can be used to gather helpful evidence and develop lessons learned for future operations. One such study by Hendershot, et al, discusses the importance of a seemingly small and insignificant incidents, for example a pipe rupture at a small plant to the chemical industry (Hendershot et al, 2003, Page 48). The importance of even a small incident is echoed by Marcus and Nichols in their work about the importance of warnings in accident prevention. Through a study of several major accidents, they discuss missed warning signs, misapplied knowledge, and the ways that information could have changed the face of the chemical industry (Marcus and Nichols, 1999, Page 483). Marcus and Nichols go on to address the importance of behaviors and capabilities, typically regarded in the nuclear industry as the safety culture of the facility, which led to potential accidents (Marcus and Nichols, 1999, Page 496).

2.5. The U.S. Chemical Safety and Hazard Investigation Board

The United States Chemical Safety Board (CSB) is an advisory group charged by Congress with the investigation of chemical accidents at fixed chemical facilities. Authorized by the Clean Air Act Amendments of 1990, the CSB became operational in January of 1998.[12] The role of the CSB, as defined by Congress, is to investigate accidents to determine the conditions and circumstances which led up to the event and identify the causes so that similar events could be prevented. The operations of the CSB are similar to the National Transportation Safety Board (NTSB); any investigation by the CSB is independent of rulemaking, inspection and enforcement of the EPA and OSHA, just as the NTSB's work is independent of the Federal Aviation Administration (FAA). Although the CSB was created to function independently of these

[12] Specifically, the authorizing legislation is in Title III of the 1990 Clean Air Act Amendments.

agencies, it typically cooperates with the EPA and OSHA to complete investigations and then provide independent recommendations to these agencies and industry.

The CSB performs root cause investigations of chemical accidents. In CSB reporting, a "root cause" can be any factor that might have prevented the accident if it had been effectively implemented prior to the accident[13]. The CSB was established as an independent agency in the Executive Office of the President specifically so that it might review the effectiveness of regulations and regulatory enforcement at several agencies, where applicable. The investigation process in the CSB includes investigators from various backgrounds: mechanical and chemical engineers, industrial safety experts, and other specialists with experience in the public or private sectors. Most of the investigators involved in the CSB have years of experience with safety in the chemical industry.

The investigation process used by the CSB is similar to that described by DOE O 225.1B above. Upon reaching the site of a chemical incident, the investigators begin to conduct detailed interviews of witnesses including plant employees, managers, and neighbors to the plant. Chemical samples and any equipment obtained from the site of the accident are sent to an independent laboratory for testing. Company safety records, inventories, and operating procedures are examined, as investigators begin the process of searching for the cause of the accident. In a process that can last several months, the investigators will evaluate the evidence

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[13] Both definitions provided by the U.S. CSB on their "About the CSB" History Page: http://www.csb.gov/about-the-csb/ (Accessed September 2013). It is noted that in DOE and NRC usage, "root cause" has a more precise definition. For instance, in DOE space, a root cause is defined as: "the cause that, if corrected, would prevent recurrence of this and similar occurrences. The root cause does not apply to this occurrence only, but has generic implications to a broad group of possible occurrences, and it is the most fundamental aspect of the cause that can logically be identified and corrected. There may be a series of causes that can be identified, one leading to another. This series should be pursued until the fundamental, correctable cause has been identified (DOE-NE-STD-1004-92)."

collected, consult with CSB Board members and review any applicable regulations and industry practices before drafting the key findings, root causes and recommendations into a report. Typically this process takes from 6 to 12 months before a draft report is submitted to the CSB Board members for consideration; comments are resolved and then these draft reports are voted upon and accepted. Differences between this process and the DOE O 225.1B include the level of independence (DOE appoints the AIB, which is still composed of DOE Federal Employees versus CSB independent investigation team), the timeframe for completing investigations, and the ability to drive change (CSB issues recommendations, which are tracked but not enforced while DOE issues corrective actions which are tracked and enforceable).

In addition to investigations of particular incidents, the CSB can also conduct evaluations or assessments of more general chemical hazards, whether or not they are directly related to an accident, similar to the DNFSB's investigations of DOE facilities. In several cases, these evaluations lead to new recommendations for chemical facilities and regulatory bodies such as OSHA and the EPA. Some examples of hazards that have resulted in more general hazard investigation include combustible dust and reactive chemicals. Typically these investigations involve several incidents at different facilities. For instance, the reactive hazards investigation looked at 150 incidents involving uncontrolled chemical reactions in industry[14].

Another major function of the CSB is the process by which recommendations are made and monitored throughout their lifetime, from issuance to closure. Recommendations made by the Board are to be justified and supported by the findings of incident or hazard investigations, the

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[14] US CSB. *Improving Reactive Hazard Management*. A hazard investigation released October 2002. Accessed via the CSB website at: http://www.csb.gov/improving-reactive-hazard-management/

review of accident trends or the conclusions of results of safety studies. These recommendations are first presented to the Board as a part of draft reports, at which point they are voted upon. By definition, a recommendation is a course of action that has been adopted by the Board and transmitted to correct an identified deficiency. Once approved, each recommendation is tracked until it is closed. Each recommendation receives follow-up activity from the CSB recommendations staff every 6 months (CSB, 2013b). Closure of a recommendation may only be achieved through voting by the Board. The recommendation process is of high importance to the CSB as it is the major tool used to transmit potential corrective actions to industry (CSB, 2013b).

CHAPTER 3

METHODOLOGY

3.1. Introduction

This chapter will discuss the general methodologies applied to this study to develop recommendations for performance measures and improvements in safety at nuclear chemical facilities. The goal of this chapter is to familiarize the reader with the methodologies employed in this research. The objectives of the chapter are to provide an overview of the database, to discuss the rationale for going beyond typical root cause analysis, to provide an overview of grounded theory development and qualitative research, and to familiarize the reader with content analysis, analytic hierarchy process, and probabilistic risk assessment.

The overall goal of this work is to create a set of potential performance and safety measures, based on past performance, the input of subject matter experts, and quantitative analysis, to help improve operating efficiency and safety at nuclear chemical facilities; thus, using data and trends analyzed from chemical industry accident reports and DOE and NRC occurrence reports to develop leading performance indicators that could drive improvements in operations. The overall framework of this study combines qualitative and quantitative insights and involves detailed review of chemical industry accident reports and DOE nuclear chemical facility occurrence reports. The goals of applying the methods described in this chapter were to develop of a comprehensive understanding of chemical and nuclear industry accidents and their most common causes, to identify commonalities and disparities in causes of accidents in the chemical industry and the nuclear industry, to develop theories from the accident database about ways to improve safety and efficiency at nuclear chemical facilities, and to identify and validate the safety and performance measures.

The most common method for accident analysis in both the chemical and nuclear industries is root cause analysis (RCA). In RCA, the person investigating and reporting on the accident typically uses causal analysis techniques to determine the causes of the accident. Root cause analysis is a process in which relevant events and conditions are identified, causal factors are identified, the deep underlying causes of the causal factors (root causes) of the causal factors are identified, and the focus is put on effective, long term solutions to these root causes (Vanden Heuvel, 2008, Page 9). Root cause analysis typically provides several areas of focus for improvement or prevention from similar causal factors recurring. All CSB accident reports contain root causes, it is one of the primary methods employed by the CSB accident investigation team.

However, RCA may not uncover the full range of causes in an accident scenario. This method may be limited by the team involved in the analysis—the outcomes of the RCA may be dependent upon the team composition, and the expertise of the individual members. For example, an expert in ergonomics may find the ergonomics of the control room to be a root cause because that is his area of expertise, while another person may find a different root cause depending on his or her expertise. Further, the root cause analysis method may oversimplify causality and the accident process or omit any indirect interactions among events (Leveson, 2011).

Therefore, while root cause analysis provides insight into some of the causes of the accident, for this study, it was necessary to go beyond the investigator identified root causes and Key Issues and examine the full text of the report to gain a full picture of the accident using the methods described in this chapter. In doing so, factors that were not previously identified root causes but contributed to the accident came to light.

This chapter is broken down into several sections that describe the methods applied in this work as follows:

3.2 Database Overview

3.3 Grounded Theory Development

3.4 Content Analysis

3.5 Analytical Hierarchy Process

3.6 Probabilistic Risk Assessment

3.2. Database Overview

While much can be gained from studying successful facility operations, it can be difficult to ascertain what problems might be lurking under the surface until these problems result in an accident. The database used for this study is composed of accident reports from the chemical industry as reported by the CSB, and occurrence reports from selected DOE and NRC nuclear chemical facilities.

3.2.1. CSB Accident Reports

60 chemical industry units of analysis were included in this work, composing the available database of chemical industry accident reports and safety bulletins released from 1998 to 2012. These chemical industry accident reports are written by the CSB staff, a combination of chemical and mechanical engineers, industrial safety experts, and other specialists with experience in the chemical industry. The reports are written as: a summary of evidence collected; applicable regulations and industry practices; interviews with plant managers, workers, labor groups, and government authorities; and root cause analysis; and recommendations (after interactions with board members).

The reports are divided into two distinct types of documents (as mentioned above): (1) the final incident reports and (2) safety information sheets and bulletins. The final incident reports include a set of Key Issues determined by the CSB and listed on the front cover of the final report, as well as: a full incident analysis, information on processes at the plant, relevant standards or regulatory analyses, findings and recommendations. These incident reports range from 10 to 300 pages, and as such, the level of detail is variable. The safety information sheets and bulletins are characterized by the combination of several incidents into one document that typically includes some lessons learned and brief summaries of the incidents. The information contained in a safety information sheet varies, depending on the timeframe in which it was written and its purpose. Some safety sheets contain Key Issues and others do not. Some go into detail about specific incidents; others are merely a general overview of a safety issue with recommendations. They address incidents that are described in detail in other final incident reports as well as some incidents for which there is no full report.

In a final chemical industry accident report, the information includes Key Issues, an introduction, details of operations, a report of any physical evidence from the accident site, an incident analysis, an overview of lessons learned and several recommendations for the industry. Safety bulletins on the other hand are more variable investigations of general chemical accident hazards. These safety bulletins typically involve the review of several previous accidents and can also lead to new safety recommendations. Recommendations are the CSB's primary method for achieving industry change and as such, the CSB maintains a record of the implementation of each recommendation and can vote to close a recommendation if its actions have been satisfactorily completed.[15]

3.2.2. DOE Occurrence Reports

The other major unit of analysis for this research was occurrence reports, from ORPS. For consistency, the occurrence reports analyzed represent the same time frame as the chemical industry accident reports, 1998 to 2012, and are associated with a nuclear chemical facility, for relevance to the overall research objective. The analysis included 47 DOE ORPS reports. The generic parts of an ORPS report include: a summary section with the name of the facility, its function, basic facility information, a significance category and building details; a notifications section with the HQ notification and other notifications organized by date and time; occurrence

[15] The current status of these recommendations includes 74% closed and only 26% open. 64% of the closed recommendations are closed by an acceptable action, and those open recommendations are largely awaiting response or evaluation (17%). CSB. (2013). *Recommendations*.

information including a subject or title, reporting criteria, criteria, operating conditions at the time of occurrence and immediate actions taken; an Integrated Safety Management System (ISM) section including cause codes, and a description of causes; a section for corrective actions; lessons learned; and a field to identify similar incidents or events.

3.2.3. NRC Abnormal Occurrence Reports

The final category of reports included in this analysis were NRC abnormal occurrence (AO) reports to Congress from fuel cycle facilities between 1998 and 2012 (to maintain consistency of the dates). During this time period, there were only four (4) abnormal occurrences reported to Congress. These abnormal occurrence reports include the criteria by which the event was deemed an AO, the date and place, the nature of the event and probable consequences, an analysis of key causes identified by the NRC, and actions taken to prevent recurrence for both the facility and the NRC.

3.2.4. Process Safety Incidents

Before being analyzed, the reports were screened to determine relevance to process safety (as opposed to industrial safety) which was used in this study to screen for significance to operations at nuclear chemical facilities. This screening was achieved through the application of the CCPS Process Safety incident guidance (CCPS, 2011). The CCPS defines an incident as a "process safety incident" if it meets all of the following criteria: 1) process involvement; 2) above minimum reporting threshold; 3) location; and 4) acute release. A flowchart CCPS recommends for identifying Process Safety Incidents is also included in Figure 3.1 (from CCPS, 2011).

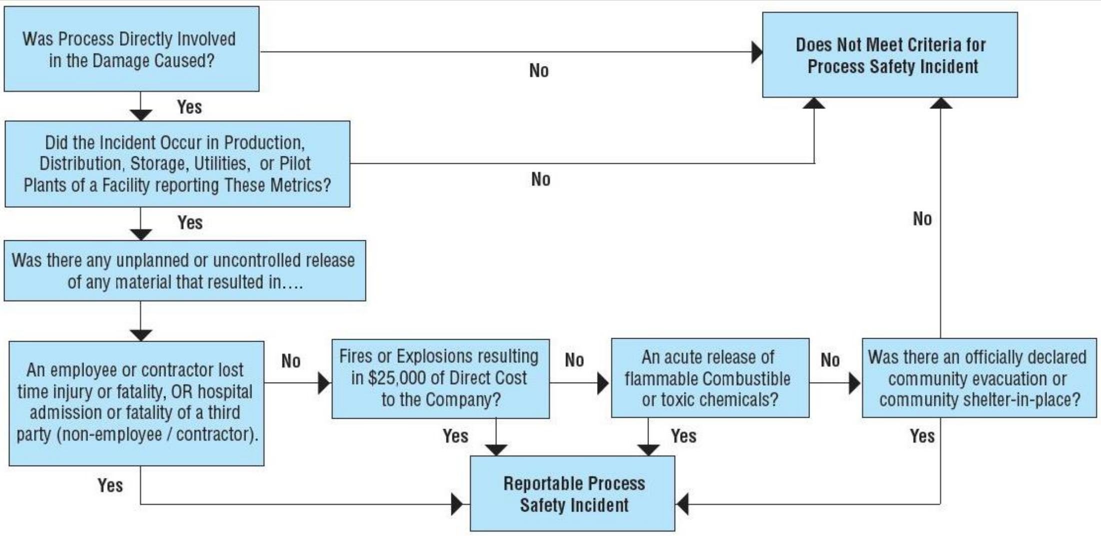


Figure 3.1 | Process Safety Incident Flowchart (CCPS, 2011)

3.3. Qualitative Analysis and Grounded Theory

Qualitative analysis, which forms a significant portion of the initial analysis used in this study, is defined as any kind of analysis that produces findings or concepts and hypotheses, as in grounded theory, that are not arrived at by statistical or quantitative methods (Glaser, 1992, Page 11). The thrust of qualitative analysis, using grounded theory, is the ability to absorb the data as data, step back and distance oneself from it, and then conceptualize the data to form theory (Glaser, 1992, Page 11).

At the most basic level, grounded theory stands in contrast to a typical research approach. Using grounded theory, the theory is developed based on data collected, as opposed to using the data to test a theory that has already been developed. This form of research is typically used in sociology, which is its primary use in Glaser and Strauss's *The Development of Grounded Theory*, but its use in this study fits well with the context; evaluating extensive amounts of textual data from accidents to develop theories on safety and efficiency of operations at similar facilities. The position of Glaser and Strauss is that generating grounded theory is a way to arrive at theory that fits its supposed uses, rather than generating theory from deduction based on previously held assumptions.

Grounded theory prevents the phenomenon described by Glaser and Strauss as *exampling*. In *exampling*, it is easy for a researcher to find several examples for any logically deduced theory, but because the idea was not derived from the examples (or a comprehensive set of data), the examples can seldom correct or change the idea. For instance, if one approached the chemical industry accident reports with the theory that a majority of accidents are caused by operator error, you could find enough accidents to prove such a theory right or wrong, but are unlikely to correct, challenge, or change this assumption. Taking the grounded theory perspective, if one takes all of the accident reports and code them, finding that a majority of the accidents are caused by operator error, you are able to develop a theory inductively, that is based on evidence and not a preconceived assumption.

In this instance, the development of theory is based on a content analysis of a comprehensive set of accident reports from the CSB, DOE ORPS, and NRC AOs. The process of content analysis and the development of theory from this review of the data is described in more detail as follows.

3.4. Content Analysis

In this implementation of grounded theory, the data was collected from each accident report using content analysis. Content analysis is a “systematic research method for analyzing textual information in a standardized way” that allows the evaluator to develop grounded theory using inferences from the information (GAO, 1996, Page 6). The main idea of content analysis is to classify and sort textual data, in this case from accident reports, into key ideas or “themes” that can be used to develop theory. This is achieved through a process of data labeling and indexing known as *coding*, or marking textual passages with shorthand notations that represent the content of original verbal information.

There were several advantages to using content analysis methodology in this study. Content analysis procedures allow for a consistent review of a large volume of material. The accidents were reported over thousands of pages of text, and content analysis allowed for consistent analysis from page to page. Further, content analysis is a systematic process—while a casual study of the material might provide insights, this methodology facilitated the consistent extraction of information. One downside of content analysis methodology is the use of judgment when coding data. It is possible that one reviewer may code a document differently than another reviewer, depending on judgments and background, leading to an inconsistency in analysis. In the case of this study, the same reviewer completed content analysis of all documents, ensuring consistency of application. The results of the content analysis were then verified using alternative means, which included: the comparison to root cause and Key Issue data, review by a second researcher, and subject matter expert review.

The following paragraph described the content analysis process. The data from the accident reports was *coded*[16] into distinct *concepts*[17] which were grouped into *categories*[18] and then used to form *theories*[19]. *Codes* are shorthand designations used in the set of data for the identification of key points. Analysis of these *codes* led to the formation of *concepts* which are collections of *codes* that can be logically grouped. Groups of similar *concepts* compose *categories* and it was these carefully constructed *categories* that explain the subject of the research in various *theories*. The *theories* developed to explain *categories* of *concepts* were used to develop performance measures for nuclear chemical facilities. An example of this structure can be seen in Figure 3.2.

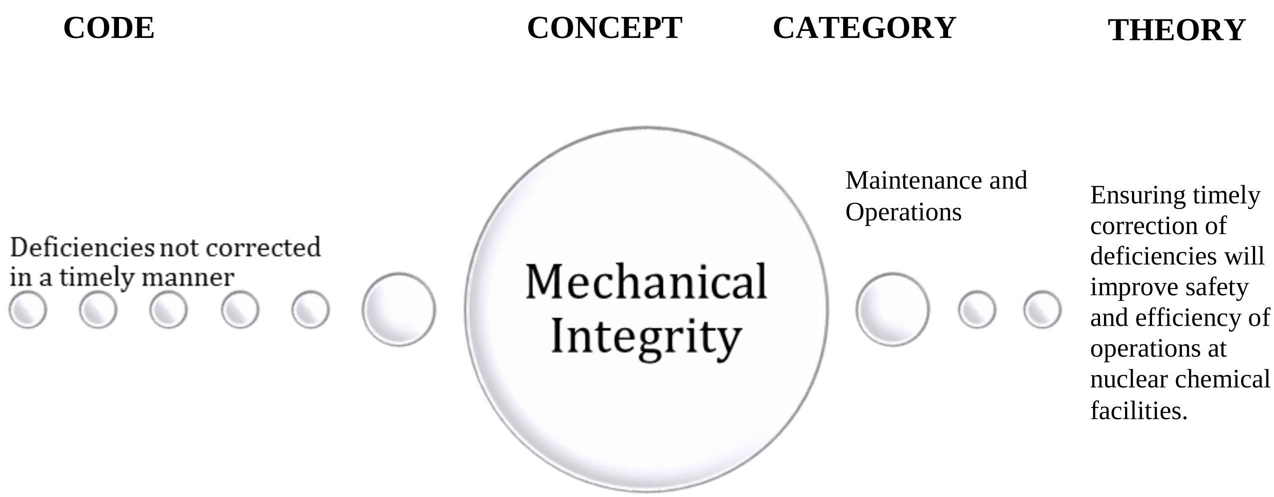


Figure 3.2 | Content Analysis Structure

[16] The process of assigning shorthand designations to a concept which can be used in the text to demarcate the presence of that concept throughout the unit of analysis.
[17] The concept is the secondary unit of description used in this analysis and represents a group of codes. Several concepts make up a category.
[18] A category is a group of concepts that share similar descriptive characteristics and thus can be grouped for enhanced explanatory power.
[19] A theory is an overall assessment formed from the data in the category form. Theory is the big picture understanding that will be developed from this research. Theories are distinguished from themes in this work as theory is developed formally using the data collected and themes are an informal representation of the data and can be derived from external sources, such as OSHA's Process Safety Management Guide.

The coding process was performed using ATLAS.ti, a software program for maintenance of *coding*, document searches and its many other functions. The content analysis software has several features which will prove useful in this analysis including: intelligent data management with external source referencing; a code manager with unlimited color-coded applications; annotated memoing functions; and auto search functions (among many others). The main advantage of using the content analysis software is that the program does the record keeping for the process. The following Figure 3.3 contains screenshot of the software program that illustrates the coding process.

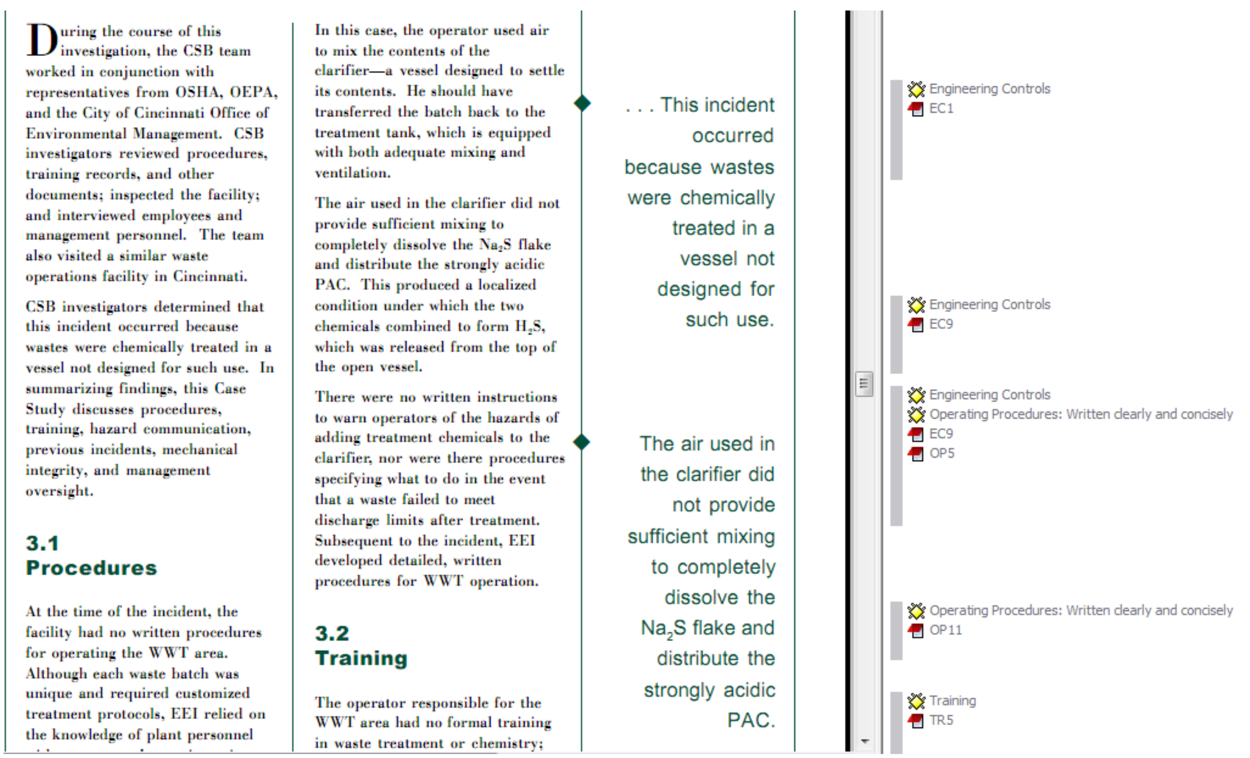


Figure 3.3 | Screenshot of Atlas.ti Coding Process

The text of the accident report, on the left, was coded using the code headings on the right with stars, and memos defining the specific instance of that code, the red notebook icons. The software program maintained the record of the selected text, the code, and the memo and then provided that information from all reports. It also maintained the frequencies of occurrence of the codes and memos. Coding the documents was an iterative process, and each report was coded and then checked for consistency with the other reports. Counting the frequency of the *codes* in the content analysis software simply involves running the program across the different units of analysis and summing total occurrences.

Finding associations between the various *codes* requires studying carefully the proximity of wording (or *codes*) in the report. The content analysis software also allows for searching various combinations of *codes* at a given time. This data will then also be evaluated by analyzing frequency of occurrence. For instance, in the text of the reports, a *code* related to hazard recognition was often followed by a *code* related to training. This means that these two issues are associated in the text, and may be connected. This process is more thoroughly described in Chapter 5 of *GAO Guidance 10.3.1*.

Ensuring a high-quality content analysis involves evaluating attributes. In selecting *categories* to use during the process, it is important to be exhaustive. An insufficient number of *categories* could lead to missing important information that could be essential to developing performance measures. Developing a coding structure from the *categories* also must be mutually exclusive for similar reasons. Each *code* will represent a single potential occurrence from a single *category* and there should be no overlap between *codes*. This can be checked by reviewing the coding manual developed during this process. There may also be inconsistencies between the types of chemical industry reports being analyzed. For instance, the safety bulletins will discuss one issue, such as reactivity, throughout the entire document which might skew the results. Thus, the frequency data of words and *codes* in the two types of documents is analyzed separately. Further details on final reporting of the coding process and more specific *code* creation methodology are described in chapter 5 of *GAO Guidance 10.3.1*. In order to ensure that a comprehensive set of *categories* have been created, the categorization process will be reviewed by a second researcher with experience in qualitative/semi-quantitative analysis.

The details of the coding process used for the chemical industry accident reports is described in Chapter 4. The process for the nuclear chemical facility accident reports is described in Chapter 5.

One tool of the methodology for this research was the maintenance of a thorough research journal in which detailed information about *coding* and *memoing*[20] was tracked back to the original coding structure. This research journal was maintained throughout the research phases. It served as a way to maintain a descriptive log of work to ensure consistency throughout each of the research objectives. A further goal of this journal was to have a record of decisions that were made regarding data collection and assignment to provide for a review by a second researcher for quality assurance purposes. Aside from consistency and maintaining a record of decisions, this journal served to record the process of the development of grounded theory through note keeping and facilitation of grouping. The research journal is summarized in Appendix A; the research

[20] Memoing is the process of writing up ideas about codes and their associations during the process of coding. This process facilitates the development of theory later in the process and serves as a way to keep track of ideas as they occur rather than attempting to recreate them after the research has been completed.

journal itself was reviewed by a second researcher with experience in qualitative/ semi-quantitative analysis.

The establishment of this coding structure followed the general analytical guidelines from Glaser and Strauss on developing theory. Substantive theory was developed from the data collected in previous research objectives. In evaluating the content of the accident reports, certain themes emerged and defined the *categories* that frequented the data set. Examining these *categories* and associations in the text, it was be determined whether a substantive *theory* for the major themes, within the context of nuclear and chemical facilities, could be developed. The substantive *theories* were area specific, while formal *theories* were for a conceptual area of inquiry. For instance, a substantive *theory* may have been specific to fire safety or emergency crew response. From these two substantive *theories*, we could then determine if a formal theory of emergency planning emerged. The precise application of theory development is described in Chapter 6.

3.5. Analytic Hierarchy Process

Once the theories had been developed, and potential performance measures based on these theories proposed, the next step was to elicit feedback from nuclear safety and operations subject matter experts on the potential performance measures to determine whether they were both practical and effective. To do this, we used a method known as Multi-Attribute Decision Analysis, and specifically, the analytic hierarchy process (AHP). AHP is a methodology of structuring, measuring, and synthesizing a decision making process, in this case used to select among competing alternatives in a multi-objective environment (Forman, 1999, Page 469). AHP was used to evaluate and prioritize the potential performance measures. It allows us to take a complex, unstructured set of decisions and break them into more manageable components, arrange them into a logical hierarchy, and compare them one by one, assigning numerical values to the variables, and synthesizing these values to determine which components have the higher value to the subject matter experts (Saaty, 2001). The hierarchy used to elicit subject matter expert feedback on the proposed performance measures had the structure illustrated in Figure 3.4, with the addition of several more categories.

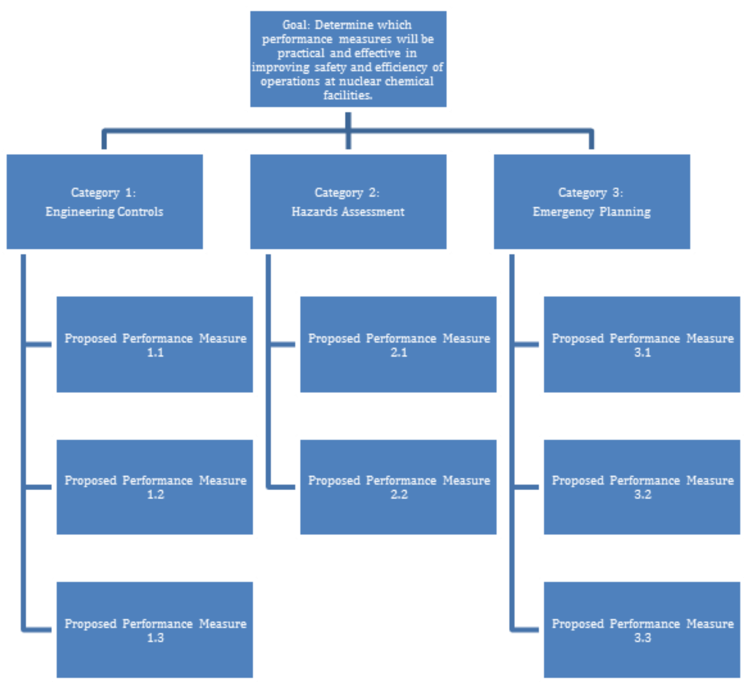


Figure 3.4 | Proposed Performance Measure Structure

In this hierarchy, the subject matter experts first analyze which categories of process safety performance measures they would prefer to use to measure safety and efficiency of operations at a nuclear chemical facility. Each of the categories, 1-3, are compared to one another. Then, under each category, they compare the proposed performance measures to one another. This process is facilitated using a computer software program, which performs the numerical calculations of the SME valuation. The software program used was Comparion by Expert Choice. This online elicitation tool is a web based program which collects input from those individuals surveyed and uses AHP to calculate group preferences based on their input. Each individual was surveyed one on one and identified by a participant number. Comparion will maintain the data and ID number of the individual participant and provide one excel file at the end of data collection with the collective comments from all users sans identifiers.

3.6. Probabilistic Risk Assessment

In order to test whether the proposed performance metrics provided a measurable reduction of risk at nuclear chemical facilities, the metrics were applied in the probabilistic risk assessment performed for the Defense Waste Processing Facility at the Savannah River Site. PRA is a tool that quantifies the outcomes of three key risk inputs—the potential failure or problem, the likelihood of that failure occurring, and the consequences if it were to occur. The tool is often used to determine the risk of operation at a specific facility, and the highest risk nodes—which may later become focus areas for risk reduction. The tool may also be used to assess adequacy of plant design and operation—it allows for the identification of potential events that dominate risk and the features of the plant that contribute to the frequency of these events. The features of the plant may be a wide array of issues such as: potential hardware failures, common-mode failures, human errors during testing and maintenance, or procedural inadequacies leading to human errors (NUREG CR-2300, 1983, Page 1-5). The following diagram in Figure 3.5 illustrates the PRA process for a nuclear reactor facility (NUREG CR-2300, 1983, Page 2-5):

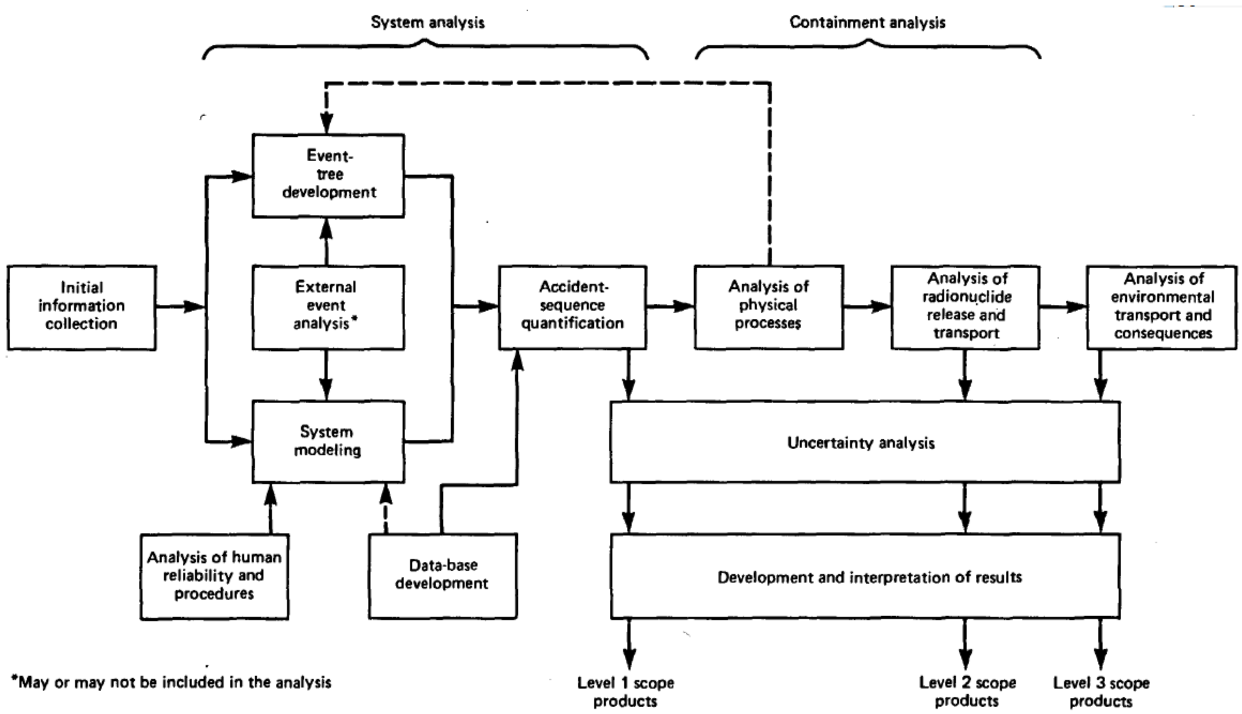


Figure 3.5 | PRA Process for a Nuclear Reactor Facility (NUREG CR-2300, 1983, Page 2-5)

The performance measures resulting from the analysis were applied to the quantification of accident sequences, and provided reduction in likelihood or consequence of the selected accident sequences for the facility, reducing the overall risk in operating the facility. The PRA for DWPF was developed and edited in this setting using a Computer Aided Fault Tree Analysis (CAFTA) program developed by the Electric Power Research Institute (EPRI). CAFTA includes and event tree modeling feature as well as a database in which to insert reliability data. Both features were helpful during this analysis. A more detailed description of the application of PRA to this study can be found in Chapter 7.

CHAPTER 4

CHEMICAL INDUSTRY ACCIDENT ANALYSIS

4.1. Introduction

The following chapter outlines the results from two analyses of the chemical industry accident reports. The goal of Chapter 4 is to describe the common causes and themes of process safety accidents in the chemical industry. This is achieved through three objectives, an analysis of the CSB identified Key Issues from the accident reports, the content analysis of chemical industry accidents, and finally, the comparison of these results.

The Key Issues analyses looked at the CSB staff identified Key Issues in chemical industry accidents with two separate lenses. The first analysis looked at the Key Issues naturalistically, using the text of the issues as they were reported. The second analysis used an OSHA Process Safety Management-centered structure to sort the Key Issues into groups based on phrasing and textual similarities. The content analysis used the methodology discussed in Chapter 3, with an OSHA PSM inspired coding structure to extract relevant data from the text of the chemical industry accident reports. The data from this analysis was then compared to the Key Issues data.

This chapter provides the chemical accident analysis results and data, as well as discussion of the trends in the chemical industry accidents studied. The data from this analysis will be combined with the data from nuclear chemical facilities, contained in Chapter 5, to develop theories about safety and efficiency of operations at nuclear chemical facilities with the goal of developing performance measures to improve safety and efficiency of operations at nuclear chemical facilities.

The outline of this chapter is as follows:

4.2 Key Issues Analyses of Chemical Industry Accident Reports
4.3 Content Analysis of Chemical Industry Accident Reports
4.4 Overall Results from Chemical Industry Accident Reports

4.2. Key Issues Analyses of Chemical Industry Accident Reports

Chemical industry accident reports provide a wealth of information that can be used to develop lessons learned to improve safety and efficiency of operations at chemical industry facilities. The CSB is one source of these accident reports. As a part of an investigation and causal analysis process, CSB investigators identify "Key Issues" for each chemical accident. This research evaluated trends in those Key Issues by applying two distinct analyses of these issues. The first analysis assessed the Key Issues naturalistically, as reported by the expert investigation team; however, this result was problematic, as about 2/3 of all Key Issues, as described in the chemical industry accident reports, occurred only once. In the second analysis, the Key Issues were sorted thematically to capture insights from the many single-occurrence issues. This thematic analysis, using categories drawn from the Occupational Safety and Health Administration's (OSHA's) Process Safety Management (PSM) guidance, allowed for a more comprehensive understanding and grouping of the issues behind the chemical accidents studied. The findings of this research identified several accident themes that can be used to develop a better understanding of chemical industry accidents and potentially improve safety and efficiency of operations at chemical facilities.

4.2.1. Key Issues Introduction

One common form of analyzing individual accidents is a causal analysis, or the determination of problems, without which the accident would not have occurred. The lessons learned through such causal analysis can be collected and shared through regulatory and industry groups to raise awareness of certain types of events with the hope of preventing similar events from occurring in the future. The CSB is an advisory group that performs a causal analysis and drafts a thorough accident report, sharing recommendations with regulators and industry and tracking the implementation of these recommendations (CSB, 2013). These chemical industry accident reports compose the database that the present work evaluated.

As a part of each accident report, and consistent with the CSB's congressional tasking to "identify contributing causes," each investigation team defines "Key Issues" which contributed to the accident. The Key Issues identified are an expert summary of the major factors contributing to the accident; they can include procedural issues ranging from the permitting of hot work to specific maintenance problems, or management issues such as a lack of organizational learning. These Key Issues are identified through a causal analysis (formal or informal), and represent factors that contributed significantly to the accident (CSB, 2013). The Key Issues act as a snapshot of the analysis from the investigation team concerning the contributing factors to each accident; as such, they provide information which can be used by chemical facilities to identify accident reports that may be applicable to their facilities, to help to improve process safety. The catalogue of Key Issues, or contributing factors, that has accumulated over the years 1998-2012 can be analyzed to identify areas of vulnerability and to develop improvement actions to enhance safety and efficiency of operations at chemical facilities.

4.2.2. Key Issues Methodology

The objectives for this work were: to analyze the Key Issues based on their qualitative characteristics, quantify the number of occurrences of Key Issues, and search for common Key Issues in chemical industry accident reports in order to potentially identify lines of inquiry to improve safety and efficiency of operations at chemical facilities. In order to accomplish these objectives, this research involved two separate analyses of the Key Issues identified in chemical industry accident reports: naturalistic and thematic. The naturalistic analysis involved a qualitative categorization of the chemical industry accident report Key Issues, verbatim. In the second analysis, a thematic analysis was performed to determine common themes that branch across several Key Issues and bring to bear more explanatory power than those developed during the first analysis. In the present study, the naturalistic analysis served as a precursor to the thematic analysis, and only the results of the thematic analysis were carried forward.

The methodology for this study used a qualitative analysis technique to initially gain insight into the causes of accidents in the chemical industry. Similar qualitative analyses have been performed on accident documentation (i.e., Gephart, 1993; Roberts, 1990; Vaughan, 1990), and provided valuable insight. The most relevant study to this work was Gephart, 1993. Gephart used qualitative data analysis facilitated by a computer to develop key word lists for study, a similar methodology to the Key Issues analysis described herein (Gephart, 1993). Another study used qualitative data available through interviews from the chemical industry security field to provide recommendations to consider for security improvements (Genserik, 2011). The results of these studies provided trends that can be used to recommend improvements, similar to the analysis described herein.

4.2.2.1. Naturalistic Analysis

In the naturalistic analysis, the Key Issues were studied as they occurred in the chemical industry accident reports; that is, exactly as they were described by the investigation team. The number of occurrences of each individual Key Issue was tallied in an attempt to identify Key Issues that were potentially common across several incident reports. It was anticipated that these commonly occurring Key Issues have the potential to offer clear and significant targets to address in working to prevent future accidents. This first analysis involved using a naturalistic qualitative method in which the unit of analysis was one chemical industry accident report. Data collection consisted of the identification of Key Issues for each document, dividing the Key Issues into related concepts and then further subdividing the identified concepts into categories. For this approach, the words in the Key Issues were used verbatim, without making any changes or assumptions. This naturalistic approach to data analysis is further described in Patton (1987). The main objective was to refrain from manipulating the data in any way during this initial evaluation, but rather to allow the data to fall into natural groupings based on similarities in wording. Performing the Key Issues analysis with a naturalistic approach was intended to capture slight differences in terminology and phrasing resulting from differences in accident circumstances. This naturalistic method is often used for the analysis of expert opinions (Glaser and Strauss, 1967). A preliminary assessment of frequently occurring Key Issues was accomplished (see Table 1 below). Unfortunately, the Key Issues from the chemical industry accident reports contain inconsistent terminology and phrasing; the naturalistic approach to the Key Issues analysis yielded over 60 distinct single occurrence Key Issues. In other words, from the reports evaluated in this research, there are 92 total identified Key Issues, 65% of which occurred only once. Examination of many single occurrence issues illustrated that numerous variations in description complicated analysis; however, similarity in overall concepts addressed indicated that more detailed evaluation of the data could produce valuable trends.

4.2.2.2. Thematic Analysis

In response to the high number of single occurrence Key Issues, a second analysis was performed in which the Key Issues were analyzed using thematic grouping. This secondary analysis smoothed out major variations in wording, and evaluated the context of the Key Issues in the reports, which allowed single occurrence Key Issues to be grouped into appropriately themed categories. By combining these categories into logical groups based on similar wording and contextual clues, clearer trend information could be extracted concerning the major foci of accidents in the chemical industry.

The focus of the thematic analysis was to develop categories based on similar wording, and then group these categories into clearly related, higher-level themes. This phase involved the development of categories that were both appropriate and meaningful. The Process Safety Management (PSM) guidelines were suggested to the authors by subject matter experts in the field, as a logical source for themes in this methodology (Occupational Safety and Health Administration, 2012). As the chemical industry is required to adhere to these OSHA guidelines, which have been in place since 2000, the PSM major headings lent themselves well to a sorting approach for the Key Issues identified in the final accident reports.

In addition, several Key Issues suggested additional themes, derived from PSM themes and refined through interviews with several industry experts. These additional themes were developed by grouping together similar issues and discussing the common themes among the groups with several industry experts. The theme of hazard recognition was derived from the naturalistic analysis as a combination of hazard recognition and hazard awareness key issues that appeared in the text. Standards issues were grouped together as a combination of standards implementation, recognition, oversight, and others. Design and engineering contemplated both engineering controls and safety systems, not covered by PSM, but a Key Issue in many accidents from the naturalistic analysis. Maintenance issues were derived from the PSM theme of Mechanical Integrity and include Key Issues of housekeeping, less than adequate maintenance, and planning of maintenance activities based on industry expert input. The themes of human factors[21] and management oversight were developed after the naturalistic analysis as well, and determined to be themes of their own. The thematic analysis structure is illustrated in Figure 4.1, and each theme is attributed to either the PSM guidelines (identified by (PSM)) or created based on naturalistic analysis with refinement from industry experts (identified by (NA)).

[21] The human factors code is not an exhaustive set of human factors issues, but rather a set of issues covered by PSM and through the chemical industry accident reports.

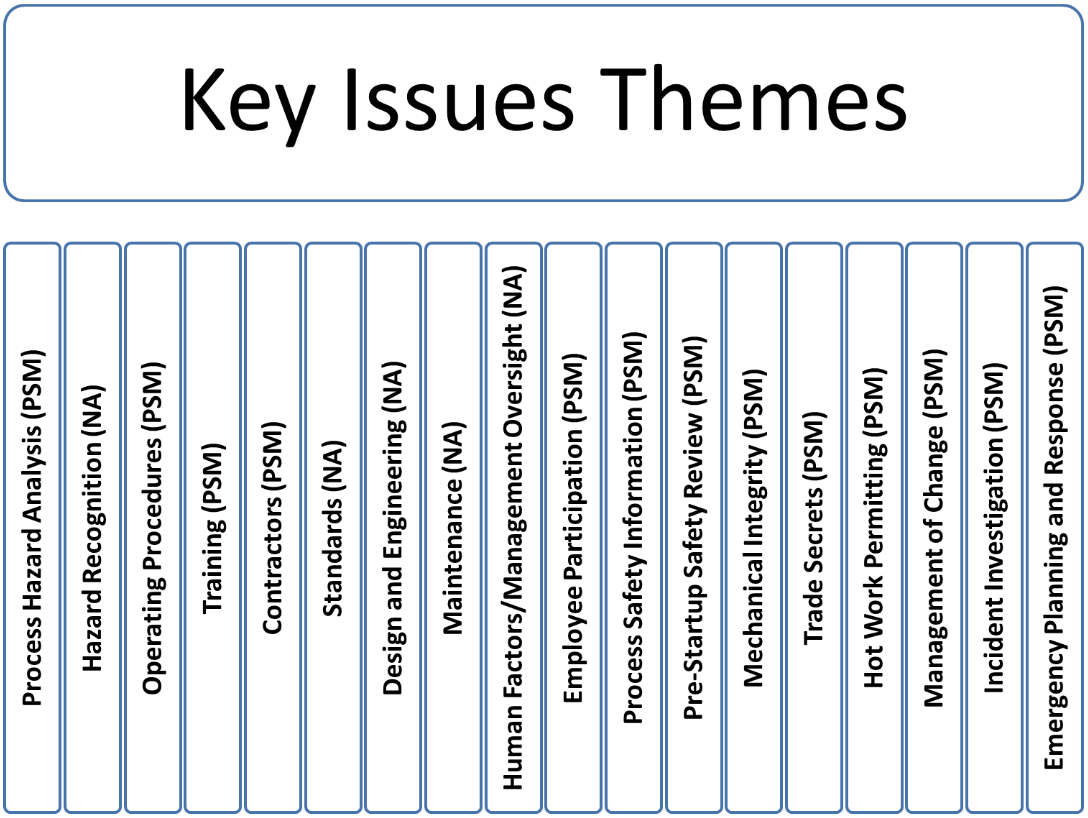


Figure 4.1 | Thematic Key Issues Analysis Structure

Once the set of themes was developed, the Key Issues data from the chemical industry accident reports were sorted into the appropriate theme. This sorting process was iterative and the placement of each topic within a theme was determined by the use of wording or phrasing similar to Key Issues in the PSM guide under the section of the rule from which the thematic heading was derived. The next step in this process involved looking for "convergence" of Key Issues; that is, those topics that could be logically grouped based on a final analysis of the Key Issue, its context in the report, and related concepts and topics identified (Glaser and Strauss, 1967).

4.2.3. Results

The results for both the Naturalistic Analysis and the Thematic Analysis of the chemical industry accident report Key Issues are described below. The two analyses of Key Issues shared some similar results. The more detailed results achieved in Thematic Analysis suggested that the more frequently occurring themes could be used as lines of inquiry for potential improvement actions.

4.2.3.1. Results for Naturalistic Analysis

Sorting the Key Issues in the first naturalistic approach yielded 93 distinct issues, 60 of which (or roughly 2/3) were represented by only one occurrence throughout the 60 reports. The results for Key Issues with a frequency of 6 or more (10%) are presented in Table 4-1.

Table 4-1 | Naturalistic Key Issue Frequencies

Key Issue	**Number of Occurrences in CSB Reports**	**Percentage of Reports Containing Key Issue (%)**
Emergency Planning, Response, and Notification	15	25.0
Equipment (or Process) Design and Scale Up	15	25.0
Regulatory Oversight	7	11.7
Process Hazards Analysis	7	11.7
Reactive Hazards and Safeguards	7	11.7
Operating Procedures	6	10.0
Accident Investigation and Lessons Learned	6	10.0

Table 4-1 illustrates the distribution of the most frequently occurring Key Issues and the relatively low number of occurrences of similarly worded Key Issues. Emergency planning, response and notification, along with equipment or process design and scale up, were both represented in the reports with a frequency of 15, meaning that these topics were considered to be Key Issues in the accident in approximately 25% of the accidents reported in the database. The next tier, with only 7 occurrences, included regulatory oversight, process hazards analysis and reactive hazards and safeguards. With 7 occurrences, these issues were prevalent in approximately 12% of the accidents reported. Other issues of note included accident investigation and lessons learned, and operating procedures in 10% of the accidents.

It is also important to note, as mentioned above, that there were 60 Key Issues with only one occurrence which led to the desire to more closely analyze this very large group of Key Issues. Many of these Key Issues appeared to share common ideas; either with more frequently encountered Key Issues or among others in this "once only" group, based on similar wording. Thus it was determined that more detailed analysis was needed, so that clearer trend information could be extracted.

4.2.3.2. Results for Thematic Analysis

In an initial, revised thematic sorting of the Key Issues, the data was placed into themes based on textual clues, and several themes were created to sort the Key Issues; the preliminary results of this thematic analysis have been presented at a conference (Morgan et al., 2012). These findings have since been refined, based on feedback received at that conference, using the PSM guidelines as the primary source of categories and combining these with several themes developed through industry experience (Occupational Safety and Health Administration, 2012).

As discussed previously, the Key Issues were then sorted into each of these new themes. The results from this analysis are presented in Table 4-2. Results presented include themes with greater than 6 occurrences (10%) in the chemical industry accident reports (as in the naturalistic analysis, above). It should be noted that twice as many themes (14) reached this frequency of occurrence in this revised analysis.

Table 4-2 | Thematic Key Issues Frequencies

Theme	**Total Number of Key Issue Occurrences**	**Percentage of Reports Containing Key Issue (%)**
Design and Engineering	27	45.0
Standards	24	40.0
Process Hazard Analysis	23	38.3
Emergency Planning and Response	22	36.7
Hazard Recognition	21	35.0
Operating Procedures	14	23.3
Maintenance	12	20.0
Management of Change	11	18.3
Mechanical Integrity	9	15.0
Process Safety Information	8	13.3
Employee Participation	7	11.7
Accident Investigation	7	11.7
Training	6	10.0
Human Factors/Management Oversight	6	10.0

As illustrated by the data in Table 4-2, the results from the thematic placement of the Key Issues differ from the previous naturalistic analysis. Design and engineering, as well as emergency planning and response, still represented two of the most frequently occurring issues; however, standards, hazard recognition, and process hazard analysis emerged as among the five (5) most frequently occurring themes in the chemical industry accident reports – each occurring in more than one-third (33%) of the reports analyzed.

Once the most common themes were identified, a closer examination of the phenomena represented in each of the Key Issues that fall under each theme was used to identify particular focus areas in which changes in process safety management could be considered. The following five (5) Key Issue themes with more than 20 occurrences, appeared in around 33% of all final accident reports in the database, and are examined more closely in what follows.

The most common theme, with occurrences in nearly half of all final accident reports studied was design and engineering. Topics in the design and engineering theme can be further divided into several phenomena. One of the typical topics in the chemical industry accident reports under this theme was a lack of a layered protection system; for instance, the existence of a single alarm system which could be compromised in an accident scenario, or a fence with no warning signs or locks. Other design and engineering topics included not incorporating accident analysis insights into design (e.g., no relief valves on pressurized tanks, no secondary alarm system), specific problems with equipment design, and scale up concerns with processes.

The standards theme was also determined to be a common theme in the chemical industry accident reports. In this theme, topics addressed were typically split between: insufficient or nonexistent regulations (with instances of enforcement issues) and a lack of oversight to ensure the standards are being followed.

Topics identified under the process hazard analysis theme related to the OSHA-prescribed process hazard assessment (PHA) which each facility is required to undergo at a minimum of every 5 years. In general, phenomena relating to the PHA were subdivided as follows: the PHA was incomplete or lacked required information, the PHA was out of date, or the PHA was not performed by an appropriate team of knowledgeable employees. The most common of these topics was the lack of information in the PHA.

In the emergency planning and response theme, the most common topics identified were related to the responsibilities of the on-site staff/management and emergency crews responding to the accident. On site, the most common topics included a lack of planning or guidance for employees and managers on proper management of emergency situations, along with instances in which the planning and guidance were in place but employees and management were not familiar with or did not adhere to the plan. Problems associated with emergency crews typically centered on a lack of understanding of reactive chemical management, a lack of preparation, or a lack of knowledge about the accident unfolding at the plant.

Hazard recognition was the final theme with more than 20 (33%) occurrences in the reports. This particular theme involved instances in which the staff and management were unable to recognize and properly respond to potential hazards at the facility. Some of the most common occurrences of this include the lack of recognition of combustible dust hazards, boiling liquid expanding vapor explosion (BLEVE) hazards, and hot work hazards.

4.3. Content Analysis of Chemical Industry Accident Reports

The Key Issues analysis provided an overview of areas deemed important by the CSB investigators, but this root cause analysis may have left out some issues important to this research. The following sections describe the content analysis of the chemical industry accident reports.

4.3.1. Content Analysis Introduction

As discussed in Chapter 3, causal analysis has some flaws; most significantly for this analysis, there could be bias introduced into the causal analysis and identification of Key Issues by the investigator. He or she may have been more inclined to find and report causes and Key Issues that were more familiar to them or their background. Further, the nature of these accident reports could lend them to bias based on the focus of safety in the chemical industry. For instance, safety culture, did not become an identified theme in the chemical industry accidents until its emergence after the BP Texas City Refinery incident.

In light of these potential biases, the best potential course of action determined was to perform a content analysis using the full text of the accident reports, to extract information that was of importance, but may not have been highlighted by the causal analysis or identification of Key Issues. This process produced results that both complemented the Key Issues analysis and provided additional insights to provide a full picture of the chemical industry accidents studied.

The following sections describe the specific application of content analysis methodology to the chemical industry accident reports, as well as the results of this analysis. The results of both analyses have been compared with those from nuclear chemical facilities, described in Chapter 5, and used to develop theories about increasing safety and efficiency of operations at nuclear chemical facilities.

4.3.2. Content Analysis Methods

The methodology for this analysis involved performing a content analysis on the chemical industry accident incident reports to provide insight into safety themes of chemical industry accidents. In content analysis, the goal was to independently identify important instances of the themes using the entire text of the reports, and then subdivide the data into codes, discussed below. This was completed in a process known as data labeling or indexing, described in detail in Chapter 3.

For this task, the unit of analysis was one chemical industry final incident report. Each report was uploaded into the content analysis software (ATLAS.ti) and coded manually. The content analysis software has several features which were useful in this analysis including: intelligent data management with external source referencing; a code manager with unlimited color-coded applications; annotated memoing functions; and auto search functions (among many others). The main advantage of using the content analysis software was that the program did the record keeping for the process. Once the chemical industry accident incident report was uploaded into the data base, automatic text searches and coding were possible. All work was auto-saved and codes (see below) documented. A single code could be run through the entire body of data with one click and the frequency of use analyzed.

A coding structure was created for this analysis and applied to each document manually using the content analysis software. Maintenance of the coding structure was essential to this work. A coding manual was maintained in the content analysis software with a list of codes and definitions as well as a document containing overall coding guidance from the process. By definition, codes are abbreviations or shorthand versions of the concepts to mark a series of text.

The coding structure for this analysis was developed using OSHA PSM and input from the Key Issues analysis and industry experts. Each code is broken down further using memos, which describe the particular issues associated with that code that can be applied in the text. The coding structure and associated memos follow over the next several pages in Tables 4-3 through 4-9. The first category of codes described relates to hazards and includes the industry expert identified code of hazard recognition, as well as the PSM code of hazards assessment (the completion of process hazards assessments and their periodic updates are required by PSM). The memos represent a catalogue of issues discovered in the data under these codes.

Table 4-3 | Hazard Codes and Associated Memos

Category	Codes	Associated Memos
Hazards	**Hazard Recognition**	HR1- Employees not made aware of hazards HR2- Hazards in design not understood HR3- Local potentially impacted people not aware of facility hazards HR4- No system or inadequate system to control hazards HR5- Hazard understood but not lessened
	Hazards Analysis	PHA1- Risks associated with the process not well analyzed PHA2- PHA inadequate PHA3- PHA does not involve literature review PHA4- PHA results not used PHA5- PHA process not defined PHA6- PHA requires revision or out of date PHA7- No PHA performed PHA8- PHA team not qualified to perform review

The second category of codes used in the analysis was standards, which was derived based on the preliminary review of the data and conversations with industry experts. Standards was the only code from this category, with many memos to represent the issues related to standards that occurred in the data.

Table 4-4 | Standards Codes and Associated Memos

Category	Codes	Associated Memos
Standards	**Adequacy**	ST1- Guidance for review of facility is insufficient ST3- Standards do not address all relevant issues ST4- Standards are not up to date ST5- Standards not well enforced ST7- Standard does not apply to a facility but should ST9- Standard does not exist
	Facility Implementation	ST2- Standards are not implemented at facility ST6- Facility or building siting ST8- Standard not applied consistently throughout facility operations and facilities ST10- Design standards not recognized or understood ST14- Standard compliance
	Oversight	ST5- Standards not well enforced ST11- Fire protection organizations do not monitor adherence to fire codes and standards ST12- No inspections to ensure implementation ST13- No actions taken from enforcement

The safety management category has several codes, all of which were derived from PSM. Pre-startup safety reviews, incident investigation, process safety information, and compliance audits all have requirements under PSM for reporting or collecting information. The memos represent the more detailed description of the issues in the data.

Table 4-5 | Safety Management Codes and Associated Memos

Category	Codes	Associated Memos
Safety Management	**Pre-Startup Safety Review**	PSSR1- Confirmation of safety systems performed LTA PSSR2- PSSR staff not experienced or knowledgeable PSSR3- Not signed off on PSSR4- Accident occurs during PSSR
	Incident Investigation	I1- Previous accidents were ignored II2- Lessons learned applied to new situations II3- Actions taken based on investigation II4- Not timely in investigation and communication II5- Other facility incidents not looked into II6- Investigations into incidents were not thorough II7- Actions and recommendations are not thorough
	Process Safety Information	PSI1- PSI not available to relevant people PSI2- PSI not used in design PSI3- PSI not comprehensive PSI4- PSI out of date
	Compliance Audits	COM1- Audits not timely COM2- Recommendations from audit not utilized COM3- Audit fails to address issue COM4- Audits not performed by knowledgeable people COM5- No program for audits exists

The maintenance and operations category contains several codes, some of which are derived from PSM and others from the data and industry experts. Hot work permitting is a PSM requirement, as is mechanical integrity, management of change, and operating procedures. Maintenance is not specifically called out in PSM, but the differentiation between maintenance and mechanical integrity was necessary to bring out important issues in the data. The memos represent the more specific issues for each code.

Table 4-6 | Maintenance and Operations Codes and Associated Memos

Category	Codes	Associated Memos
Maintenance and Operations	**Hot Work Permitting**	HW1- Flammable conditions inside a container HW2- Permits signed and checked HW3- Lack of controls for HW
	Mechanical Integrity	MI1- Inoperable equipment MI2- Lack of preventative maintenance program MI3- Equipment issues caused by accident worsened accident conditions MI4- Inspections and tests performed after the fact MI5- No MI procedures in place MI6- Equipment repeatedly causes issues MI7- Inspections and tests too infrequent MI8- Corrosion or degradation of materials MI9- Lack of inspection plans MI10- Deficiencies corrected in timely manner MI11- Inspections and tests did not find issues MI12- No inspections performed MI13- Equipment or conditions not checked before startup
	Management of Change	MOC1: Shift turnover changes MOC2- reconfiguration without instructions MOC3- Employees informed of changes

		MOC4- incorrect characterization of big change as subtle change MOC5- Prompt MOC process MOC6- Change effects not fully understood MOC7- Procedures not established MOC8- Procedures adjusted with changes MOC9- MOC review not performed
	Maintenance	MA-1: Maintenance not alerted of issue MA-2 Maintenance software issues MA-3 Maintenance plan is LTA MA4- Performance of maintenance LTA MA5- Housekeeping is LTA MA6- Communication about maintenance tasks MA7- Maintenance spending MA8- Endangerment of maintenance workers
	Operating Procedures	OP1- Inadvertent addition of material not in procedure OP2- Procedure does not contain clear instructions for a part of the process OP3- Procedure not followed by operators OP4- Procedures rely on memory of facility workers and are not written OP5- No procedure for abnormal conditions OP6- Procedure does not contain PSI OP7- Procedure includes equipment no longer in service or obsolete OP8- Inconsistent procedures used by different operators OP9- Revisions to operating procedures OP10- Procedures not analyzed for safety OP11- No written procedure

Engineering controls are not expressly covered under PSM, but there were two clear demarcations of engineering controls issues in the text: engineering controls and safety systems. These two codes were derived from the data and input from industry experts. The memos represent the associated issues in the text.

Table 4-7 | Design and Engineering Codes and Associated Memos

Category	Codes	Associated Memos
Engineering Controls	**Engineering Controls**	EC1- System does not contain design features necessary for safe operation EC2- Physical failure due to underdesign EC3- Failure to control equipment EC4- Materials or equipment design issues EC5- Represented need for more engineer participation in design or process EC6- Design drawings or information not complete EC7- System to correct design deficiencies EC8- Design hazard recognition EC9- System not installed according to design or other requirements EC10- Engineers or professionals participation in design process and knowledge of design standards EC11- Scale up issues EC12- Computer Controls EC13- Building siting EC14- Manufacturing defect
	Safety Systems	SS1- Failure to wear PPE SS2- Lack of remote equipment for process safety SS3- Ventilation system insufficient SS4- Failure of a backup safety system (cooling) SS5- Lack of controls (layers of protection) SS6- Lack of alarm system

		SS7- Reliability of safety controls SS8- Nuissance alarms or desensitization to alarms SS9- Pressure relief devices SS10- Fire protection systems SS11- Vehicle controls SS12- Emergency lights SS13- Personnel safety equipment (safety showers)

The human factors category includes four codes. Contractors, training, and employee participation are covered by PSM. Management oversight is not directly covered by PSM, but was an issue in the data. The memos represent the associated issues in the text.

Table 4-8 | Human Factors Codes and Associated Memos

Category	**Codes**	**Associated Memos**
Human Factors	**Contractors**	CON1- Poor communication between contractors and operators CON2- Contractor understanding of process safety CON3- Unauthorized contractor work
	Training	TR1- Employees not trained in use of maintenance requests or maintenance TR2- Training lacks process safety information (use of cautions and warnings, equipment purposes etc) TR3- Refresher training provided for hazards TR4- MOC training TR5- Training is largely informal and may not cover all situations TR6- Training not offered with enough frequency TR7- Lack of training records TR8- No training offered on a particular piece of equipment or process TR9- Training not well planned or designed TR10- Inspector training for compliance TR11- Simulation training or training methods ERT1- Emergency response crews participate in training with real drills and process information
	Management Oversight	MO1- Managers on site MO2- Manager knowledge of process and design MO3- Manager sign off and approve process MO4- Management implements process safety actions MO5- Managers lack safety concern
	Employee Participation	EP1- Employees participate in incident investigation and planning of actions to correct incident conditions EP2- Employees participate in work planning

The final category used in the content analysis of chemical industry accident reports was emergency planning and response. This category was covered in PSM, both the planning and response. For the sake of the analysis, the data was coded separately for the two issues, emergency planning and emergency response. The associated memos detail the issues for these codes in the text.

Table 4-9 | Emergency Planning and Response Codes and Associated Memos

Category	Codes	Associated Memos
Emergency Planning and Response	**Emergency Planning**	EPP1- Lack of emergency plan EPP2- Drills relating to plan performed EPP3- Plan clarifies roles and responsibilities EPP4- Failure to account for all personnel EPP5- Failure to sound alarm system EPP6- Community and other responders aware of and involved in emergency planning EPP7- Failure to follow plan EPP8- Information for response and treatment of injured
	Emergency Response	ERR1- Failure to establish safety of environment at facility ERR2- Offsite responders participate in drills ERR3- Site information shared with emergency responders ERR4- Community evacuation issues ERR5- Communication issues with local emergency response ERR6- Assistance necessary from additional emergency crews ERR7- No one assigned to point person ERR8- Offsite crews injured ERR9- Insufficient resources ERR10- Desire to help others overwhelms training or response instinct

In the semi-quantitative data analysis, the frequency of codes and memos were studied. Counting the frequency of the codes in the content analysis software involved running the program across the different units of analysis and summing total occurrences. The total occurrences for each individual report were also be investigated as some reports had many occurrences of a word or phrase, indicating its importance in that incident, but due to the length of the report, or number of times the code occurred, it seemed more important than other codes that appeared in more incidents.

Associations between codes were also analyzed. Associations are defined as relationships between codes in the database, typically determined by the content analysis software. Finding associations manually between the various codes required studying the proximity of wording (or codes) in the report. The content analysis software also allows for searching various combinations of codes at a given time.

Content analysis of the chemical industry accident reports was an iterative process. The reports were coded multiple times to ensure consistency and eliminate double counting. The coding guide, provided in Appendix A, was refined as the coding process went on, and relied upon to maintain consistency during the iterations of the process.

4.3.3. Content Analysis Results

The overall results of the content analysis are illustrated in the following Figure 4.2. The results illustrate the percentage of chemical industry accident reports in which each code occurred.

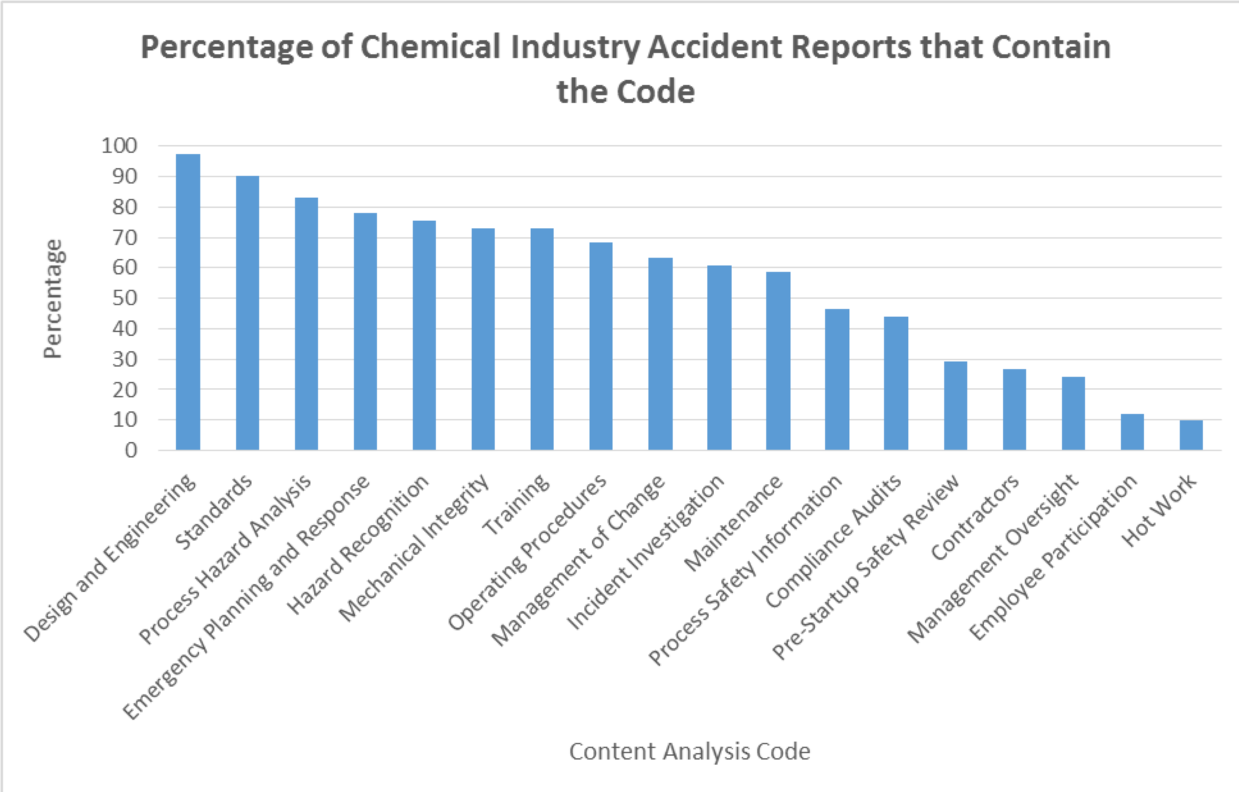


Figure 4.2 | Overall Results of the Content Analysis

In Figure 4.2, many of the codes are represented in more than half (50%) of the chemical industry accidents. These codes include Emergency Planning and Response (78%), Design and Engineering (98%), Hazard Recognition (76%), Incident Investigation (61%), Maintenance (59%), Management of Change (63%), Mechanical Integrtiy (73%), Operating Procedures (68%), Process Hazards Analysis (83%), Standards (90%), and Training (73%). The high prevalence of the represented codes in the chemical industry accident reports was illustrative of a coding structure that encompasses a large section of the issues in chemical industry accident reports. The codes listed above were identified as issues in more than half of the process safety accidents studied, and provided a starting point for the development of theories about accidents and safety at facilities with complex chemical operations.

The more detailed results of the content analysis are presented in the following sections by category.

4.3.3.1. Content Analysis Codes for Hazards

The following sections describe the results for Hazards Codes.

4.3.3.1.1. Content Analysis Results for Hazards Recognition

Hazard Recognition codes appeared in 76% of the studied chemical industry accidents. These codes were further broken down using the memos described in the methodology as follows in the chart in Figure 4.3.

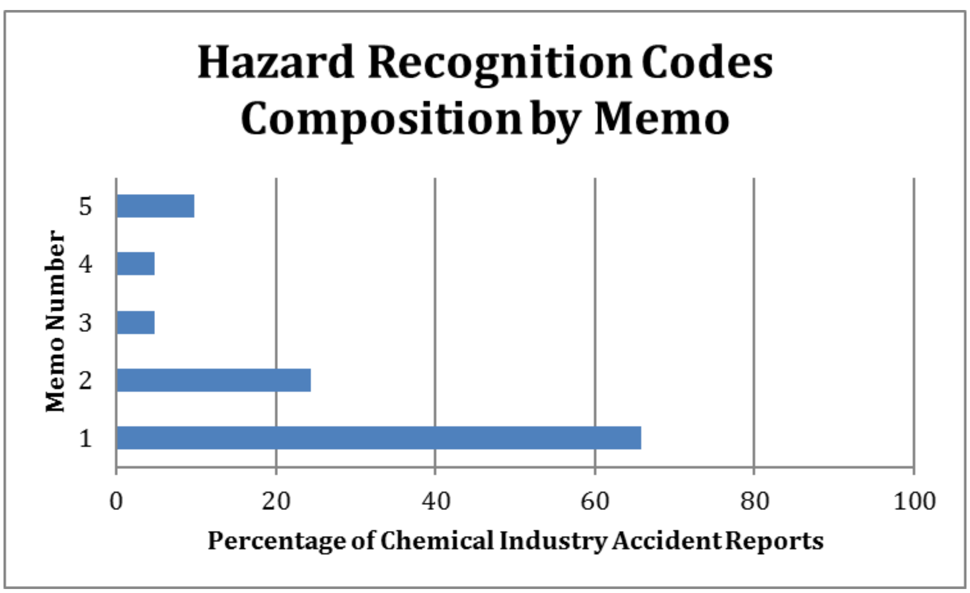


Figure 4.3 | Hazard Recognition Code and Associated Memos

The most common issue associated with hazard recognition, which composed a large portion of the instances of the code, was HR1- Employees not aware of hazards. This issue was found in 66% of the chemical industry accidents and was frequently associated with training codes, process hazards analysis codes, and process safety information codes. Also of note, with 22% was HR2- Hazards in design not understood. This typically was associated with Design and Engineering codes and related to a lack of understanding of innate hazards in the design of the system or facility.

4.3.3.1.2. Content Analysis Results for Hazards Analysis

Hazards Analysis codes appeared in 83% of the studied chemical industry accidents. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.4.

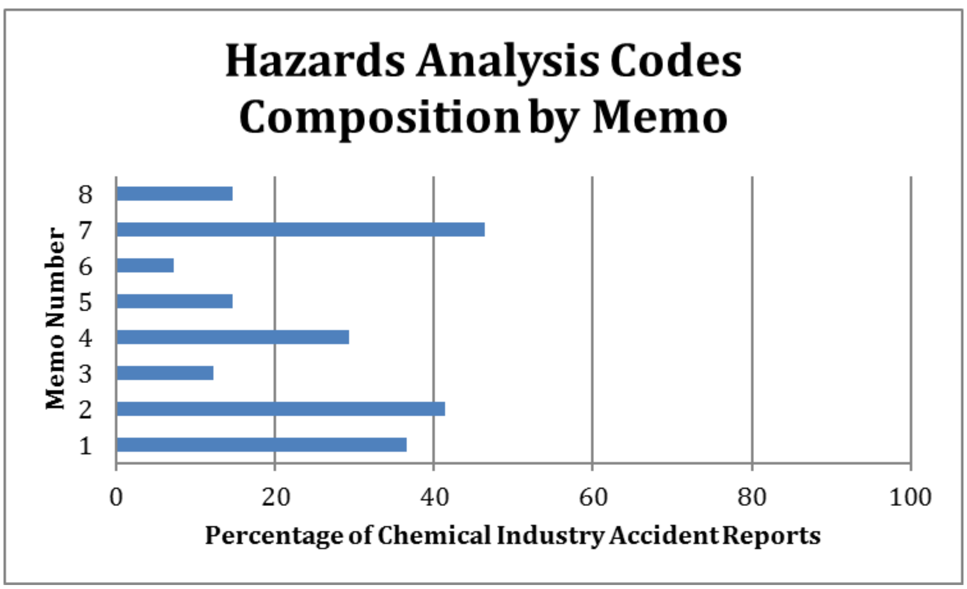


Figure 4.4 | Hazards Analysis Code and Associated Memos

The most frequently occurring memo related to hazards analysis was PHA7- No PHA performed on the system. This memo occurred in 46% of the reports and illustrated a lack of planning and consideration for hazards at the facility. This issue should be less of a problem at nuclear chemical facilities, which are required to undergo hazards analysis in order to operate. The more likely issue for nuclear chemical facilities, which occurred in 41% of the chemical industry accidents studied, was an inadequate PHA that did not cover the relevant hazards. This may be particularly useful at nuclear chemical facilities where the focus tends toward radioactivity hazards rather than chemical hazards. Associations with hazards analysis codes tended to be safety systems and training.

4.3.3.2. Content Analysis Results for Standards

Standards codes appeared in 90% of the studied chemical industry accidents. This is a logical place for the CSB to spend some time in the content of their reports, as they make many recommendations to regulators concerning the content and enforcement of standards, as well as to sites about adhering to regulations. These codes were further broken down into issues using the memos described in the methodology as follows in the charts in Figures 4.5-4.7.

Standards codes tended to be strongly associated with other standards codes in the analysis.

4.3.3.2.1. Content Analysis Results for Standards Adequacy

The standards adequacy code is further broken down into issues, using the memos described in the methodology, as follows in the chart in Figure 4.5.

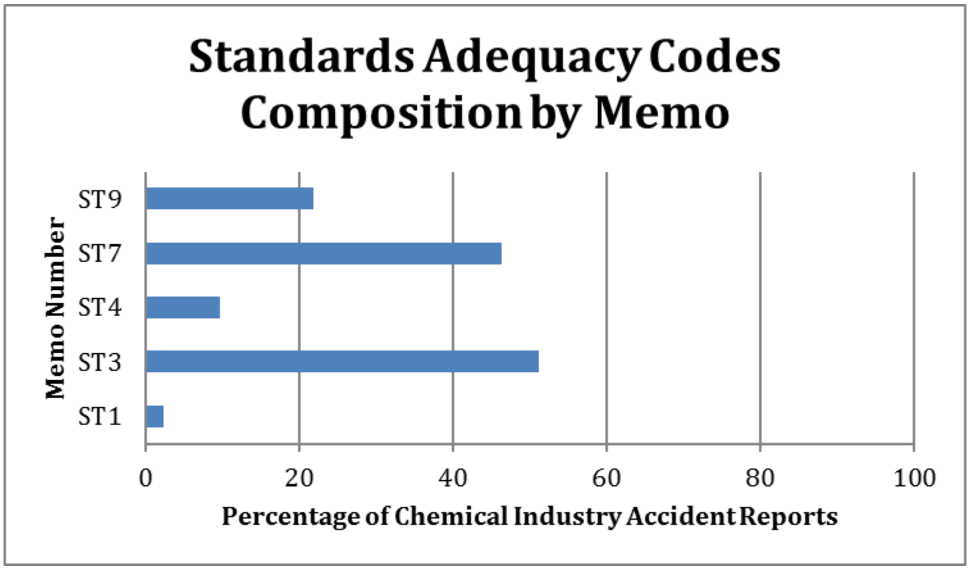


Figure 4.5 | Standards Adequacy Code and Associated Memos

Standards Adequacy issues were represented by two major codes. ST3- Standards do not address all relevant or necessary issues also occurred in over half (51%) of the chemical industry accident reports. This memo indicated that the issues were not solely the fault of the facility, but may also be a problem with the regulator. ST7- Standard does not apply to a facility but should was also a frequently occurring code, occurring in 46% of the chemical industry accident reports.

Associations with Standards- Adequacy codes included Design and Engineering and other Standards issues.

4.3.3.2.2. Content Analysis Results for Standards Facility Implementation

The standards facility implementation code is further broken down into issues, using the memos described in the methodology, as follows in the chart in Figure 4.6.

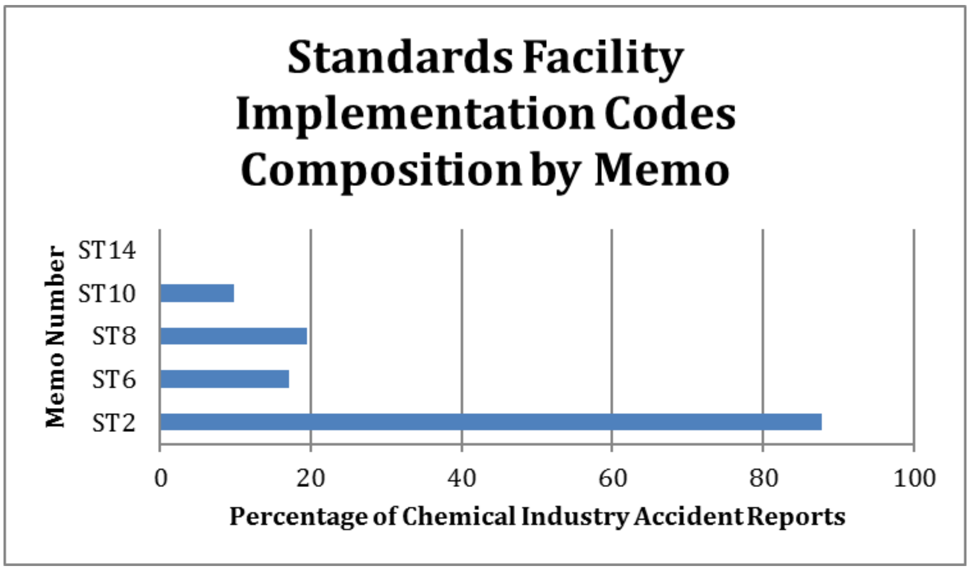


Figure 4.6 | Standards Facility Implementation Code and Associated Memos

One standards issue stood out from the others in its presence in 88% of the chemical industry accidents studied in this analysis: ST2- Relevant standards are not implemented at this facility. For the majority of the accidents studied, this memo was the effect of PSM or RMP not being implemented at a facility in which it should have been implemented, or not fully implemented (the facility followed outdated regulations).

Associations with Standards-Facility Implementation codes included Design and Engineering, and Process Hazard Analysis.

4.3.3.2.3. Content Analysis Results for Standards Oversight

The standards oversight code is further broken down into issues, using the memos described in the methodology, as follows in the chart in Figure 4.7.

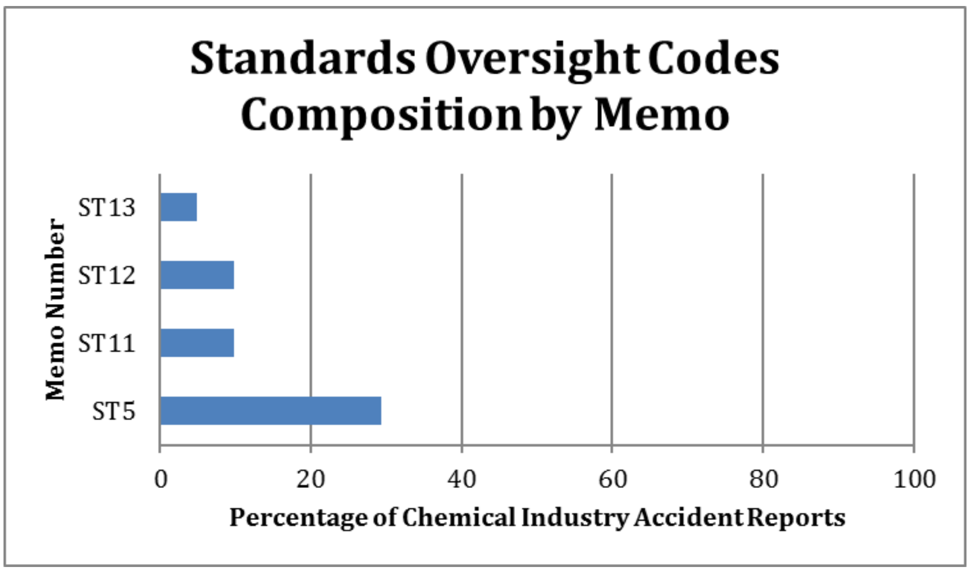


Figure 4.7 | Standards Oversight Code and Associated Memos

Standards Oversight memos were less common in the chemical industry accidents studied. ST5- standards not well enforced, was the most frequently occurring memo (29%). The other memos were less prevalent, occurring in no more than 10% of the analyzed chemical industry accidents. There were few associations with Standards-Oversight codes, mainly including other Standards issues.

4.3.3.3. Content Analysis Results for Safety Management

The following sections describe the results for Safety Management codes.

4.3.3.3.1. Content Analysis Results for Pre-startup Safety Review

Pre-startup Safety Review codes appeared in 29% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.8.

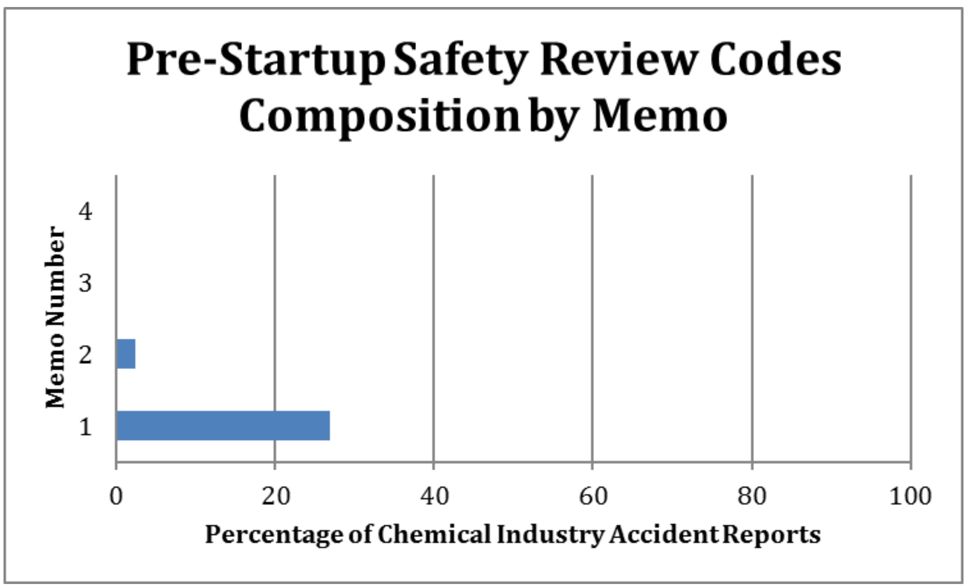


Figure 4.8 | Pre-startup Safety Review Code and Associated Memos

The most common issue associated with a pre-startup safety review, occurring in 27% of the chemical industry accidents studied, was PSSR1- the confirmation of safety systems was performed less than adequately. This code was associated with safety systems. The issue other issue that occurred in the chemical industry accident reports was PSSR2- the staff performing the review was not knowledgeable about the process.

This issue was associated with training and human factors codes.

4.3.3.3.2. Content Analysis Results for Incident Investigation

Incident Investigation codes appeared in 61% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.9.

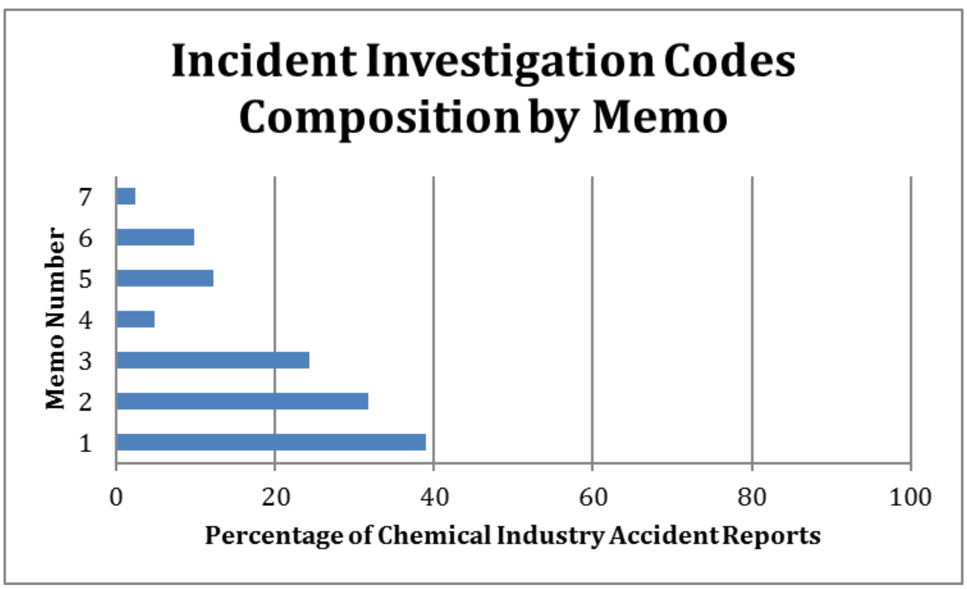


Figure 4.9 | Incident Investigation Code and Associated Memos

Occurring in 39% of the studied chemical industry accident reports was memo II1- Previous accidents were ignored. In other words, in about 1/3 of the accidents studied, there was a precursor accident, or several, that occurred leading up to the event that was reported on, that could have been studied to improve process safety, and apply lessons learned that might prevent recurrence, but these events were not adequately evaluated and/or corrective actions were ineffective.

II2- Lessons learned applied in new situations occurred in 32% of the studied accidents. This informed us that in another 1/3 of the accidents studied, precursor accidents had been investigated, and lessons learned developed, that were then not applied to the facility. This happened in a combination of ways, the most common being the facility did not use the operational experience obtained by its company, or it did not research prior incidents at similar facilities, where information was available.

The most common associations with II codes tended to be process hazard assessments and process safety information.

4.3.3.3.3. Content Analysis Results for Process Safety Information

Process Safety Information codes appeared in 46% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.10.

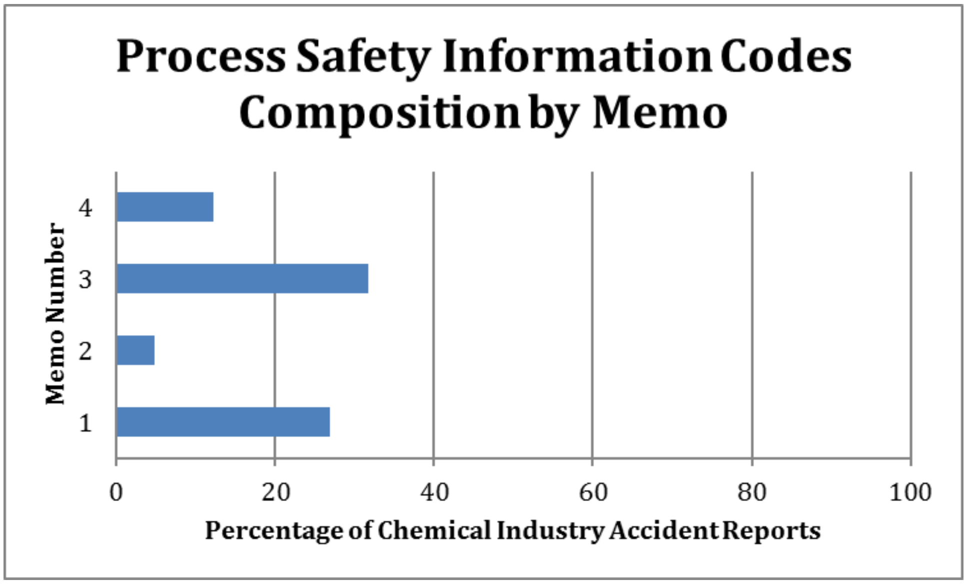


Figure 4.10 | Process Safety Information Code and Associated Memos

Process Safety Information codes were fairly evenly split between PSI1- Process safety information not available to relevant people (27%) and PSI3- Process safety information not comprehensive (32%).

The most common associations with PSI codes tended to be operating procedures and hazard recognition. In some cases, without process safety information, the operators were unable to make a determination about the operations of the facility, or made an assumption about operating conditions, such as temperature or pressure, which resulted in the accident.

4.3.3.3.4. Content Analysis Results for Compliance Audits

Compliance Audits codes appeared in 44% of the chemical industry accident reports. In the analysis, the compliance audit code was used to signify any audit (not just OSHA PSM audits, as the code name might imply). The audits referenced may have been performed by OSHA, the company management, or another party. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.11.

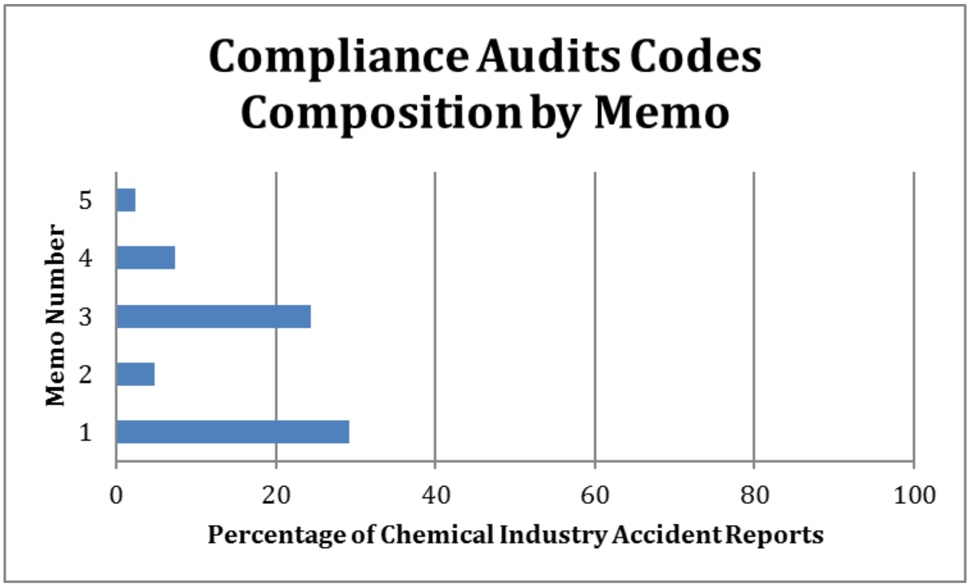


Figure 4.11 | Compliance Audit Code and Associated Memos

COM1- Audit not timely was an issue in 29% of the studied chemical industry accident reports. Under PSM, OSHA has the capability to perform audits at a facility; but, due to staffing limitations and the sheer number of facilities addressed, OSHA and affiliated state agencies do not have the resources to perform these reviews. In many of the accidents studied, the audit had been scheduled for a time after the accident occurred.

The other common issue within the compliance audits code, COM3- Audit fails to address issue, occurred in 24% of the studied accidents. This memo marked situations in which an audit did occur in a timely fashion, but was not thorough, or in some way missed a problem, which ultimately resulted in the accident.

Audit issues were associated with standards codes and in some cases, training codes.

4.3.3.4. Content Analysis Results for Operations and Maintenance

The following sections describe the results for Operations and Maintenance codes: mechanical integrity, management of change, maintenance, operating procedures, and hot work permitting.

4.3.3.4.1. Content Analysis Results for Mechanical Integrity

Mechanical Integrity codes appeared in 73% of the chemical industry accident reports. These codes were further broken down into issues using the memos, described in the methodology, as follows in the chart in Figure 4.12.

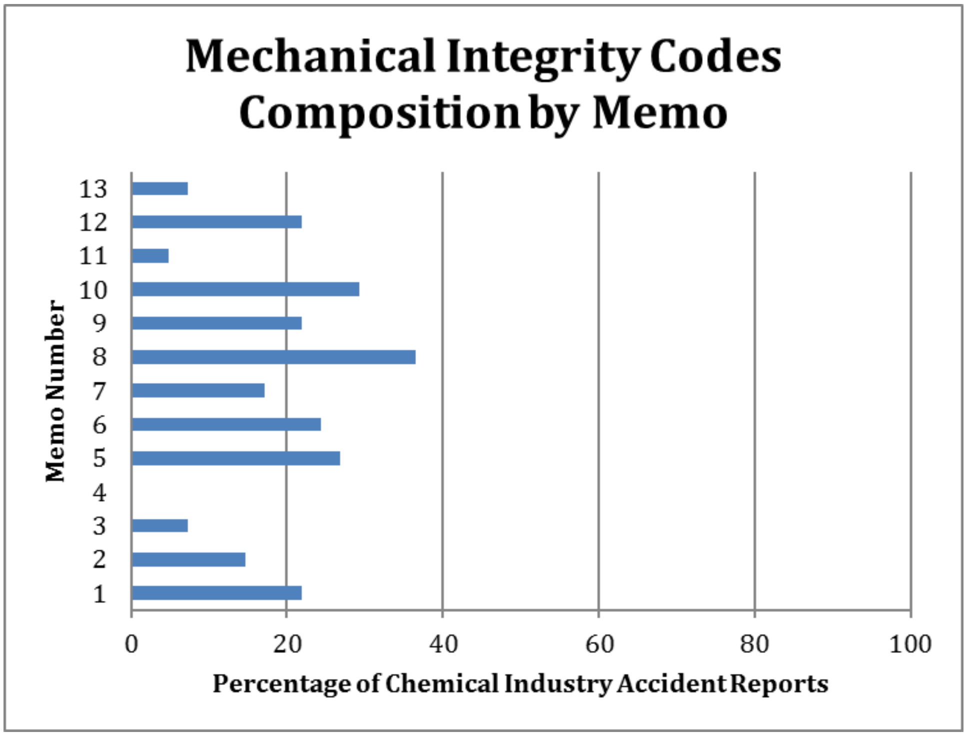


Figure 4.12 | Mechanical Integrity Code and Associated Memos

Mechanical integrity issues were fairly widespread and evenly split in the chemical industry accident reports, representing a broad range of mechanical integrity problems that could occur in a chemical facility. The most common issue was MI8- Corrosion or degradation of materials which occurred in 37% of the studied chemical industry accidents. MI10- Deficiencies not corrected in timely manner occurred in 29% of the studied accidents; MI5- No MI procedures in place occurred in 27%; and MI6- Equipment repeatedly causes issues occurred in 24%. Two of these top occurring mechanical integrity issues (MI8 and MI6) shed light on an issue that is also common at nuclear chemical facilities— aging and degrading facility conditions and equipment. The others, (MI10 and MI5) are tied to planning procedures and scheduling mechanical integrity checks and replacement of necessary components. Further, three issues related to inspections and tests: MI1- Inspections and tests did not find issues, MI9- Lack of inspection plans, and MI12- No inspections performed all occurred in 22% of the studied accidents.

Mechanical integrity issues were associated with maintenance and management oversight.

4.3.3.4.2. Content Analysis Results for Management of Change

Management of Change codes appeared in 63% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.13.

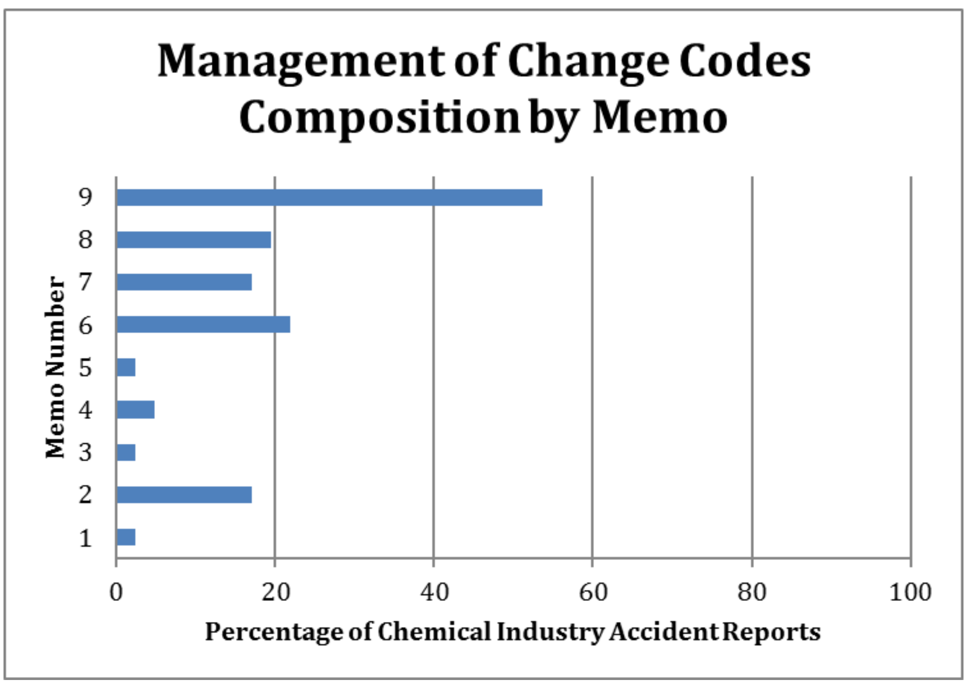


Figure 4.13 | Management of Change Code and Associated Memos

By far, the most common issue associated with management of change codes was MOC9- MOC review not performed which occurred in 54% of the studied chemical industry accidents. This highlighted a major issue in chemical facilities, where processes and procedures can shift over time. MOC6- Change effects not fully understood occurred in 22% of the studied accidents, and MOC8- Procedures adjusted with changes occurred in 20%. MOC2- reconfiguration without instructions and MOC7- Procedures not established both occurred in 17%.

Management of change codes tended to be associated with engineering design codes, training codes, and operating procedures.

4.3.3.4.3. Content Analysis Results for Maintenance

Maintenance codes appeared in 59% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.14.

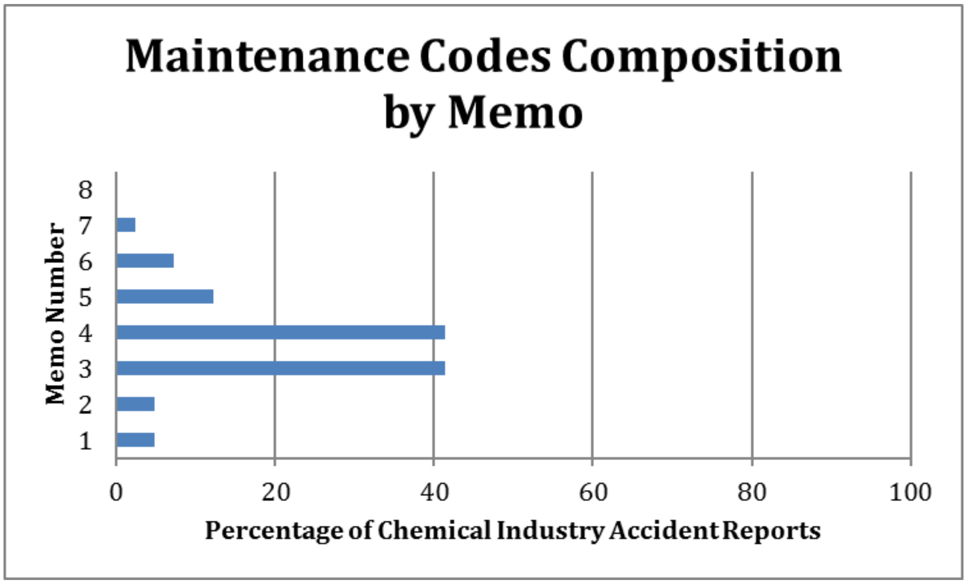


Figure 4.14 | Maintenance Code and Associated Memos

Two maintenance issues, MA3- MA-3 Maintenance plan is LTA and MA4- Performance of maintenance LTA each occurred in 41% of the studied chemical industry accident reports. These two issues highlighted the necessity for maintenance planning and to ensure that right resources (both staff and finances) were focused on maintenance.

Also of note, some of the instances of maintenance were combustible dust explosions, in which housekeeping plays an integral role, thus the inclusion of MA5- Housekeeping LTA which occurred in 12% of the studied accidents. In these cases, the LTA housekeeping was an identified root cause of the accident.

The maintenance issues were most frequently associated with mechanical integrity codes. Maintenance of systems plays a large role in maintaining the mechanical integrity, and a system with poor maintenance processes tended to face the mechanical integrity issues described previously.

4.3.3.4.4. Content Analysis Results for Operating Procedures

Operating Procedures codes appeared in 68% of the chemical industry accident reports. These codes were further broken down into issues, using the memos described in the methodology, as follows in the chart in Figure 4.15.

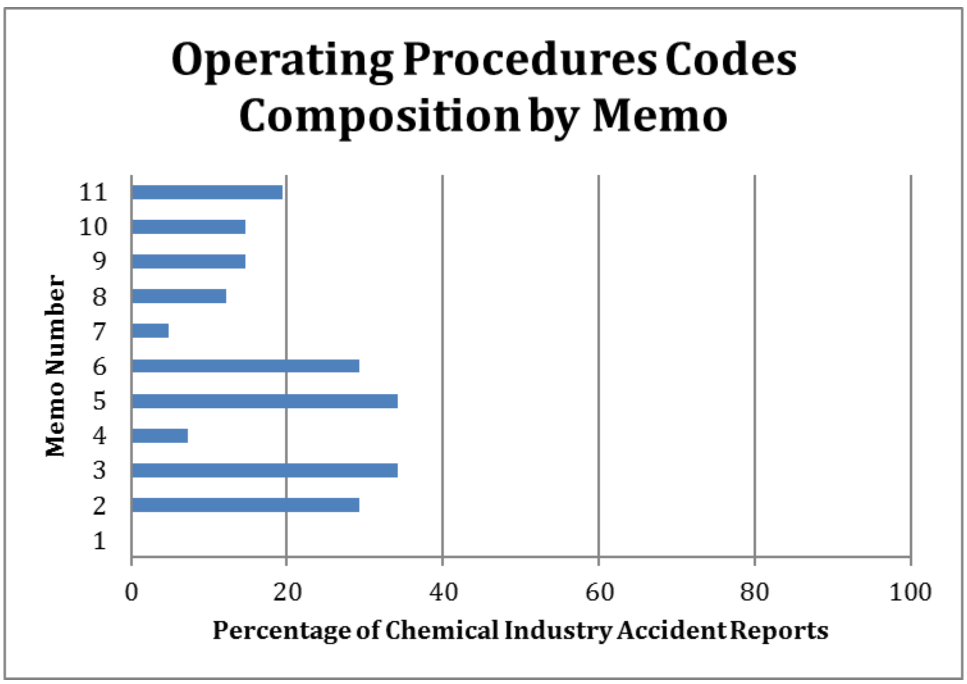


Figure 4.15 | Operating Procedure Code and Associated Memos

Occurring in 34% of the studied chemical industry accident reports, OP3- Procedure not followed by operators and OP5- No procedure for abnormal conditions highlight the necessity of including operators in the procedure process. When operators did not follow procedures, there was no written instruction for how to complete the work, and therefore no consistency, and no record of any changes that may have been made. Where procedures did not contain information for abnormal operation conditions, such as elevated temperature or pressure in a reactor vessel, the operators were left using process knowledge or education to develop a fast response, rather than clear, fact based instructions.

OP2- Procedure does not contain clear instructions for a part of the process and OP6- Procedure does not contain PSI were also high frequency issues, occurring in 29% of the studied chemical industry accident reports. These two issues highlight the need for procedures that contain all relevant operational information. The procedures should contain step by step instructions for the process, as well as information about the process that may be required.

Operating procedures issues were typically associated with training, process safety information, and employee participation, as well as hazards recognition.

4.3.3.4.5. Content Analysis Results for Hot Work Permitting

Hot Work Permitting codes appeared in 10% of the chemical industry accident reports. These codes were further broken down into issues using the memos, described in the methodology, as follows in the chart in Figure 4.16.

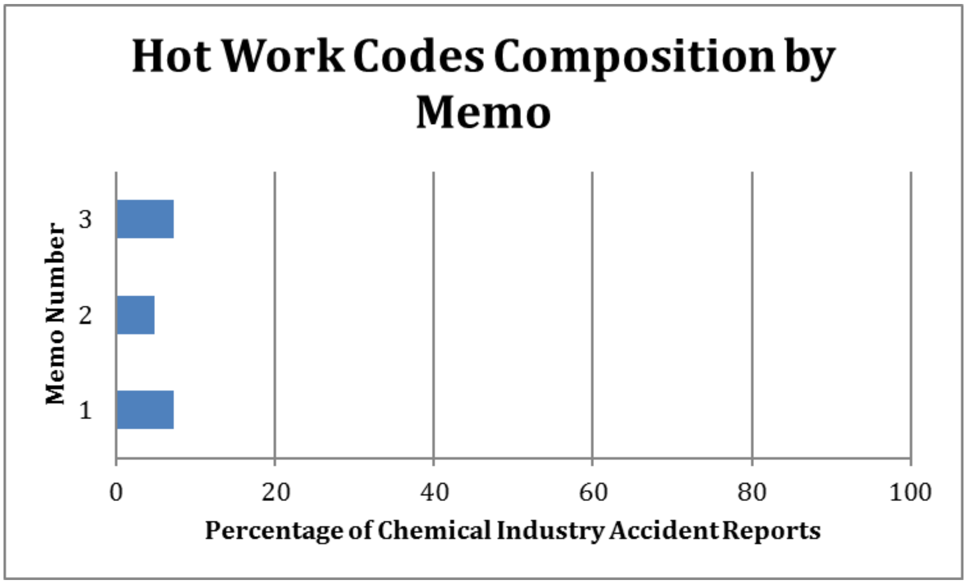


Figure 4.16 | Hot Work Code and Associated Memos

Hot work issues were evenly divided among 3 areas, although they occurred in less than 10% of the total chemical accidents studied. Occurring in 7% of the accidents, HW1- Flammable conditions inside a container and HW3- Lack of controls for HW were the most common, with HW2- Permits not signed and checked occurring in only 5% of the accidents. Hot work issues were not frequently the cause of the accident itself, but were going on when the accident occurred.

HW1 and HW3 issues tended to be associated with hazard recognition; the person performing the hot work was not aware of the flammable conditions and therefore did not apply any standard hot work controls to the process.

4.3.3.5. Content Analysis Results for Design and Engineering

Overall, Design and Engineering codes appeared in 98% of the chemical industry accident reports. These codes include both Engineering Controls, and Safety Systems.

4.3.3.5.1. Content Analysis Results for Engineering Controls

Engineering controls appeared in 90% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.17.

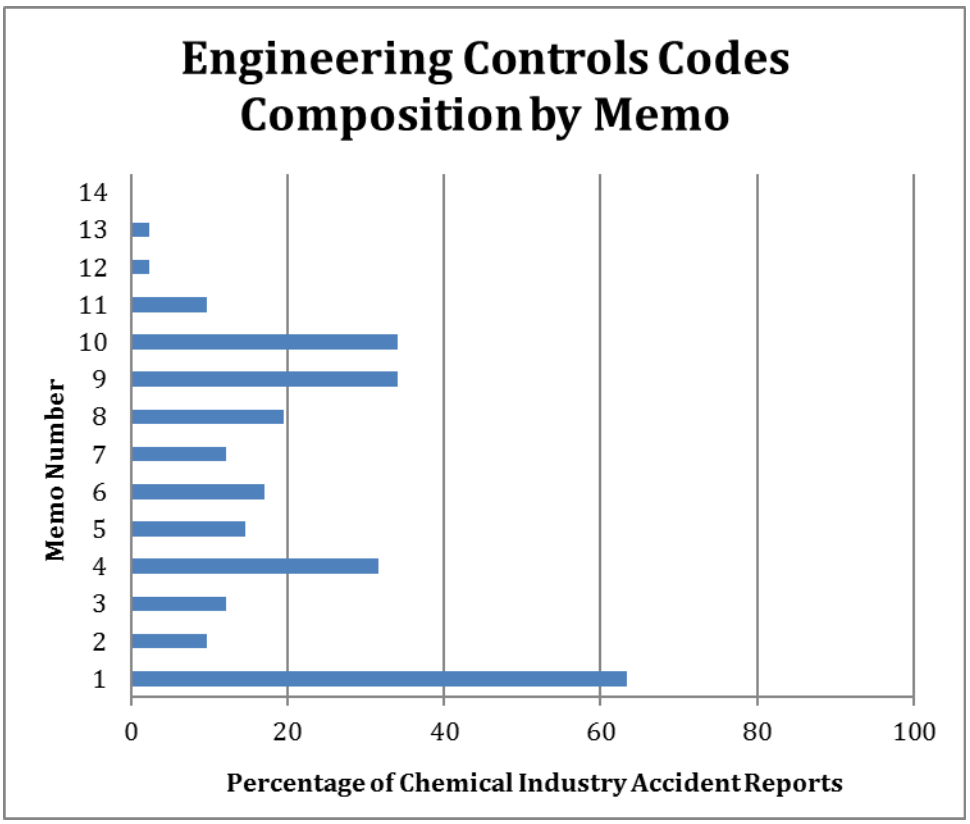


Figure 4.17 | Engineering Control Codes and Associated Memos

A wide range of issues composed the engineering controls code, from the design process to the capabilities of the process equipment. Occurring in 63% of the studied chemical industry accidents, EC1- System does not contain design features necessary for safe operation was the most common engineering controls issue. This issue highlights the necessity of the design process and focusing the right resources on the front-end to ensure a safe, operational system on the back-end. This issue is echoed in EC4- Materials or equipment design issues, EC9- System not installed according to design or other requirements, and EC10- Engineers or other professional participation in design process, which all occurred in about 30% of the accident reports.

Strong associations with engineering controls included hazards recognition codes.

4.3.3.5.2. Content Analysis Results for Safety Systems

Safety systems codes appeared in 83% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.18.

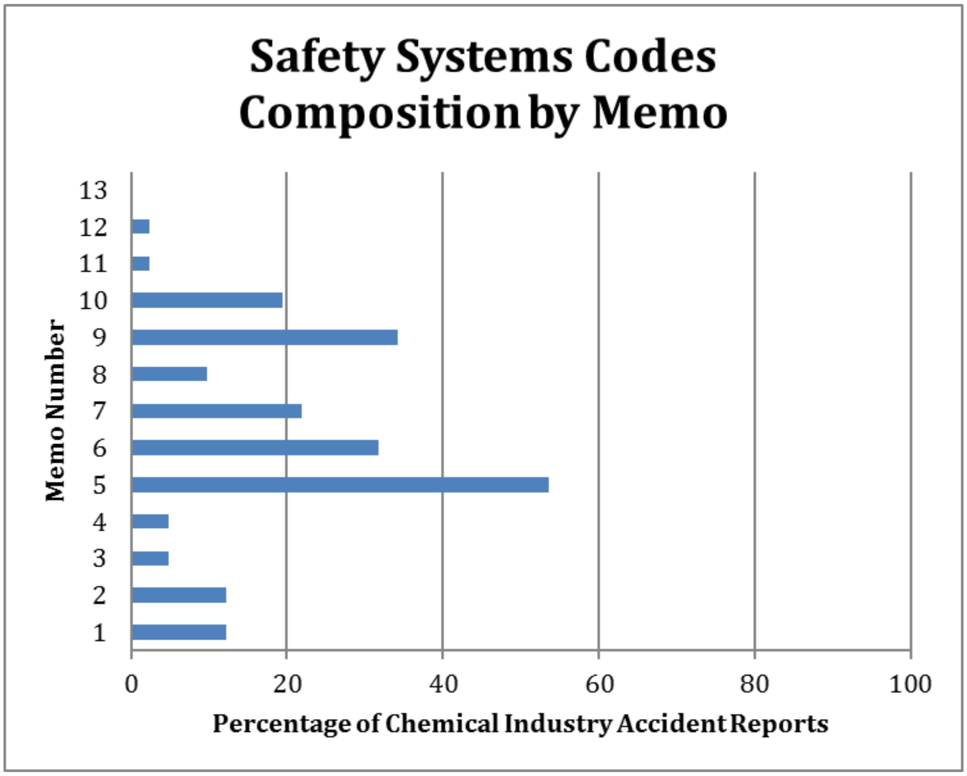


Figure 4.18 | Safety System Codes and Associated Memos

SS5- Lack of controls occurred in 53% of the studied chemical industry accident reports. These issues were related to a lack of safety controls designed into the process, or insufficient layers of protection for the system. SS9- Pressure relief devices issues, and SS6- Lack of alarm systems were also noteworthy in 34% and 32% of the chemical industry accidents studied, respectively. These highlighted particular systems or subsystems which were insufficient at the facilities and either caused or worsened the effects of the accidents. A typical issue with pressure relief devices was their failure—they did not function as intended or designed. The most common issue with alarm systems was the lack of one where it was necessary.

Common associations with safety systems issues were hazards codes and engineering control codes.

4.3.3.6. Content Analysis Results for Human Factors

The following sections contain the results for Human Factors codes: Contractors, Training, Management Oversight, and Employee Participation.

4.3.3.6.1. Content Analysis Results for Contractors

Contractors codes appeared in 27% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.19.

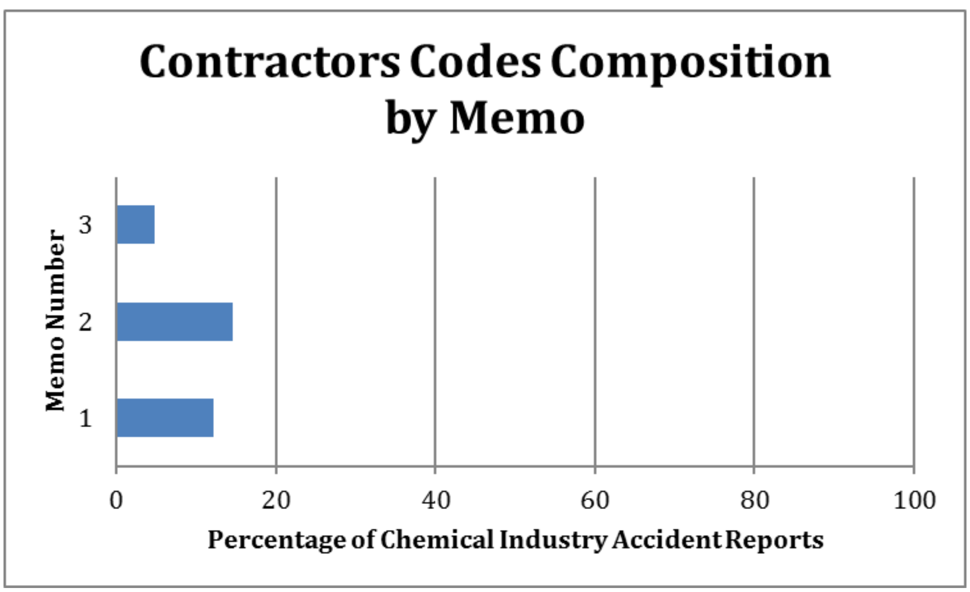


Figure 4.19 | Contractor Code and Associated Memos

CON2- Contractor understanding of process safety occurred in 15% of the studied chemical industry accident reports. This issue was related to contractors coming in to a facility and working without understanding the process and/or associated hazards. CON1- Poor communication between contractors and operators occurred in 12% of the studied chemical industry accident reports. In the accidents in which these contractor issues occurred, contractors typically wound up being injured or killed.

Contractor issues had associations with training and hazard recognition.

4.3.3.6.2. Content Analysis Results for Training

Training codes appeared in 73% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.20.

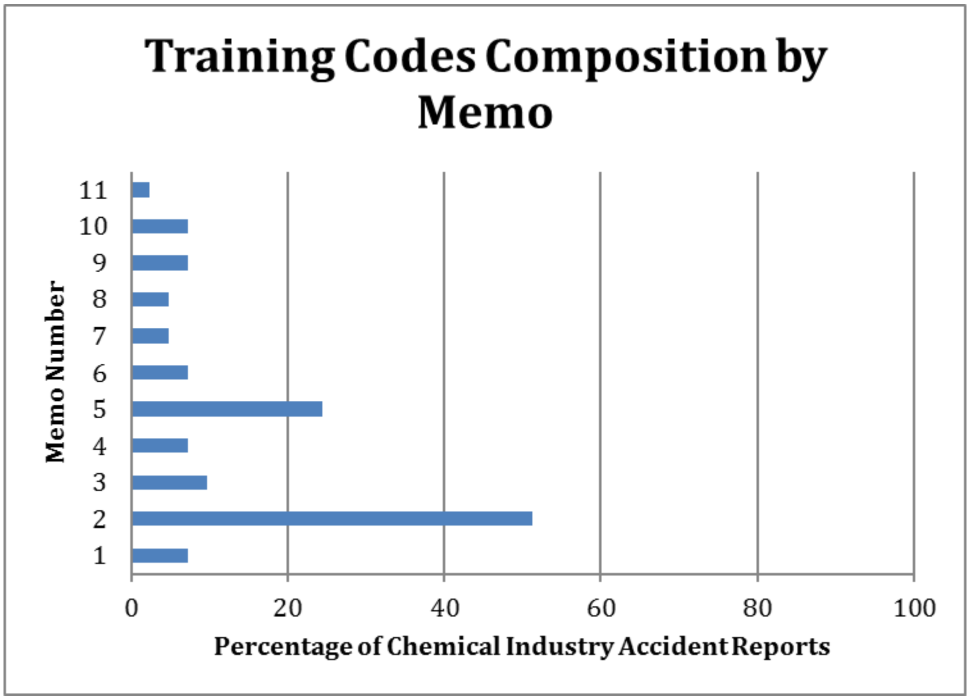


Figure 4.20 | Training Code and Associated Memos

Training issues were numerous in the chemical industry accident reports (73%). TR2- Training lacks process safety information (use of cautions and warnings, equipment purposes etc.) occurred in more than half (51%) of the studied chemical industry accidents. In this issue, the association between training and process safety information highlights the importance of workers understanding the process and hazards associated with it. TR5- training is largely informal and may not cover all situations occurred in 24% of the studied chemical industry accidents. This issue highlighted the necessity of formal training programs to ensure comprehensive coverage and adequate completion.

Codes associated with training were process safety information, operating procedures, and hazard recognition.

4.3.3.6.3. Content Analysis Results for Management Oversight

Management Oversight codes appeared in 24% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.21.

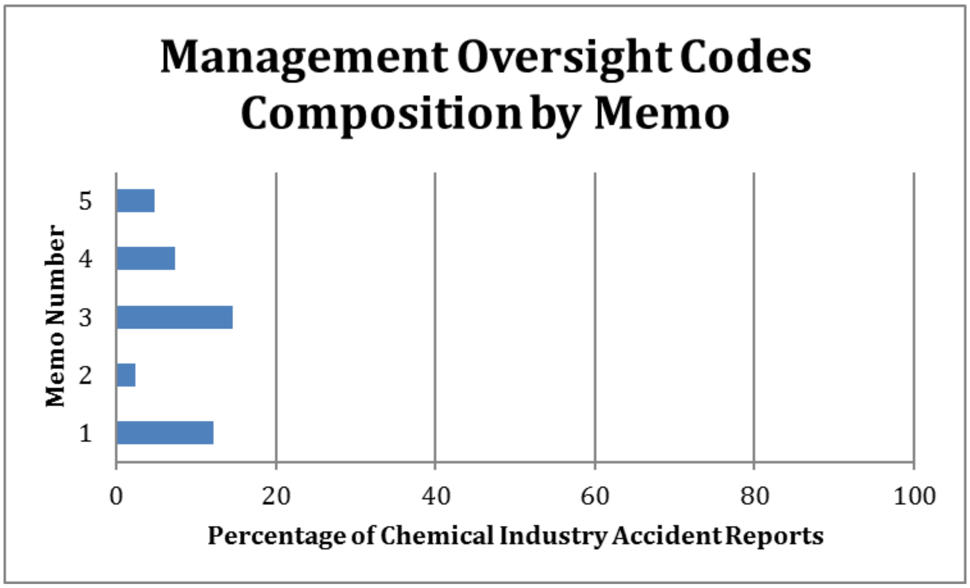


Figure 4.21 | Management Oversight Code and Associated Memos

Management oversight issue MO3- Manager sign off and approve process occurred in 15% of the studied chemical industry accident reports. This issue represented a lack of management participation in process development and operation. MO1- Managers never on site occurred in 12% of the student reports. This issue represented a lack of management time spent in the field, or on the floor with the operators.

Associations with management oversight codes included operating procedures, hazard recognition, and employee participation.

4.3.3.6.4. Content Analysis Results for Employee Participation

Employee Participation codes appeared in 12% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.22.

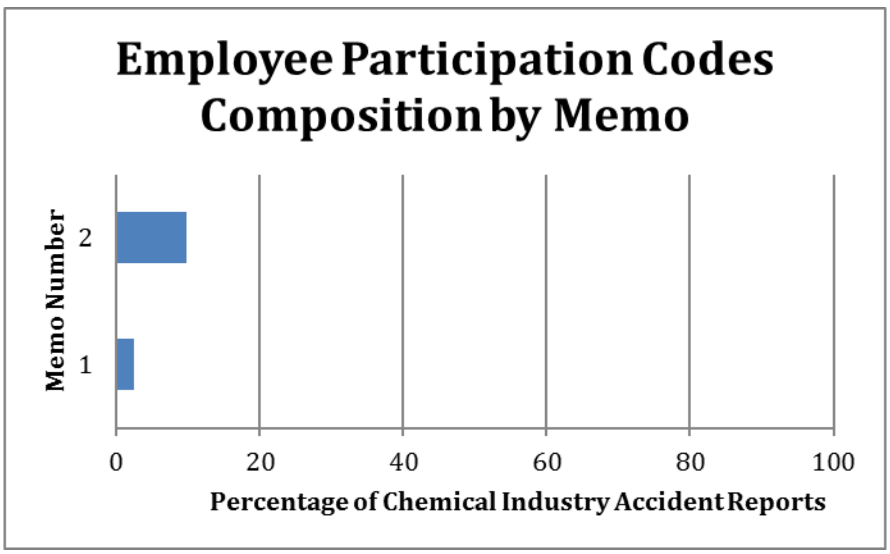


Figure 4.22 | Employee Participation Code and Associated Memos

The majority of instances of the employee participation code were EP2- Employees participate in work planning, which was an issue in 10% of the studied chemical industry accidents. Typically, employees were not allowed the opportunity to participate in work planning which resulted in an error in the performance of the work.

Associations with employee participation codes included management oversight and hazard recognition.

4.3.3.7. Content Analysis Results for Emergency Planning and Response

Emergency Planning and Response codes appeared in 78% of the chemical industry accident reports. The codes were divided into two areas, Emergency Planning, and Emergency Response.

4.3.3.7.1. Content Analysis Results for Emergency Planning

Emergency Planning codes appeared in 39% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.23.

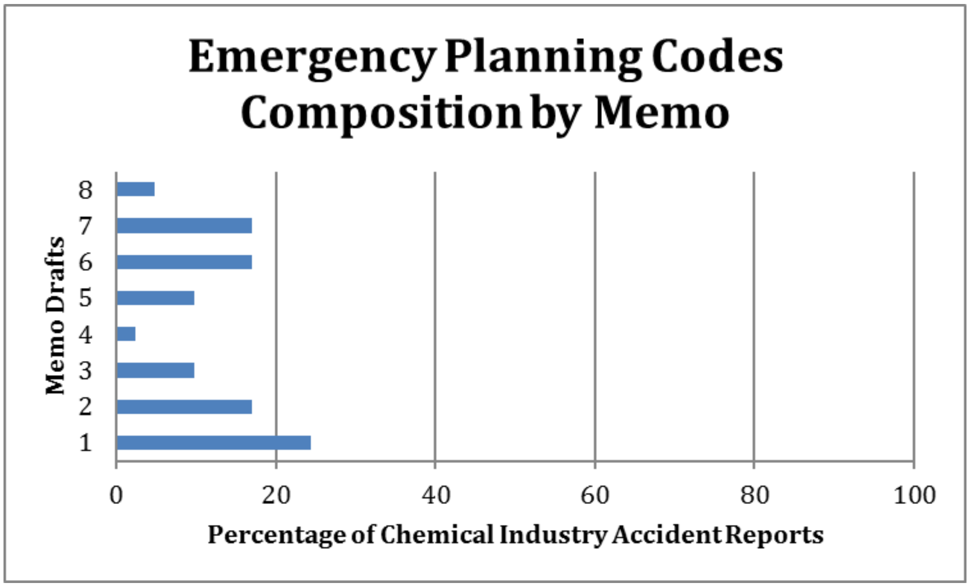


Figure 4.23 | Emergency Planning Code and Associated Memos

In 24% of the studied chemical industry accident reports, EPP1a-Lack of emergency plan was the most common emergency planning issue. In other words, 25% of the facilities involved in accidents did not have an adequate emergency plan. While this would be less of an issue at nuclear chemical facilities, at which emergency plans are required by DOE O 151.1, Comprehensive Emergency Management System, there may be some value in updating the plan (also required by DOE O 151.1) and ensuring the plan adequately covers potential accidents.

EPP1b- Drills relating to plan performed and EPP3c- Community and other responders aware of and involved in emergency planning were also important issues in this area, occurring in 17% of the studied accidents. These two areas are intertwined with the importance of including local emergency responders and site emergency responders in drilling and planning.

Associated codes with emergency planning included training and hazard recognition.

4.3.3.7.2. Content Analysis Results for Emergency Response

Emergency Response codes appeared in 71% of the chemical industry accident reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 4.24.

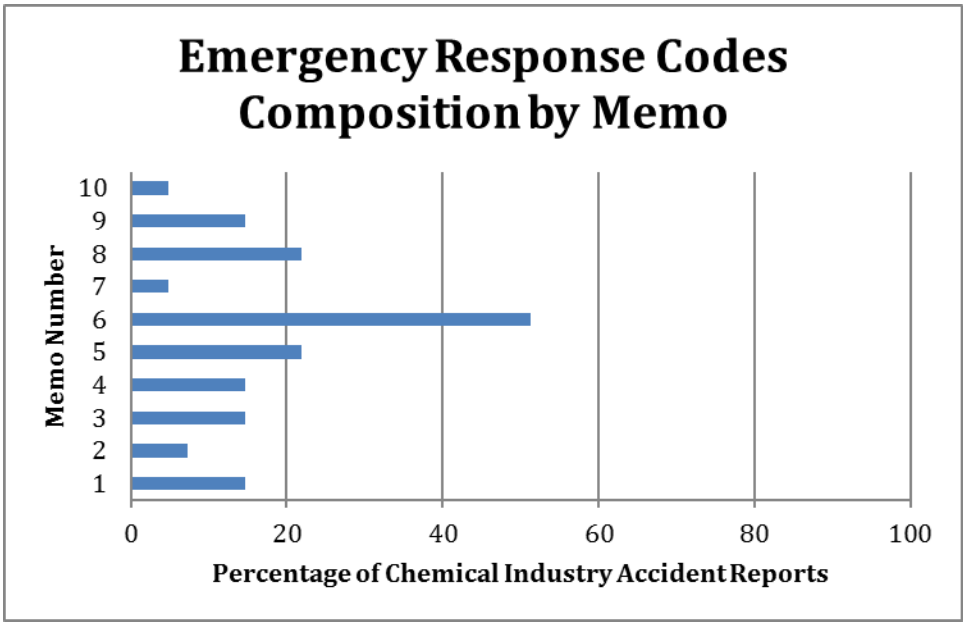


Figure 4.24 | Emergency Response Code and Associated Memos

The most common issue in emergency response was ERR6- Assistance necessary from additional emergency crews which occurred in 51% of the chemical industry accidents. This was indicative of the lack of onsite emergency response capability, and subsequently, reiterated the importance of working with the local emergency responders, such as fireman, policeman, and hospitals, to ensure a well-practiced and smooth response. This was further highlighted in ERR5- Communication issues with local emergency response and ERR8-Offsite crews injured at 22%.

Local responders need to be aware of the hazards at the facility and how to respond to them, and communication with them needs to ensure safety for them and the community. This is a particularly important area in the analysis, as emergency responders made up a majority of the fatalities and injuries in the studied reports.

Codes most frequently associated with emergency response codes were hazard recognition and training.

4.4. Overall Results from Chemical Industry Accident Analysis

The overall results from the Key Issues and content analysis of the chemical industry accident reports are compared in the following Figure 4.25.

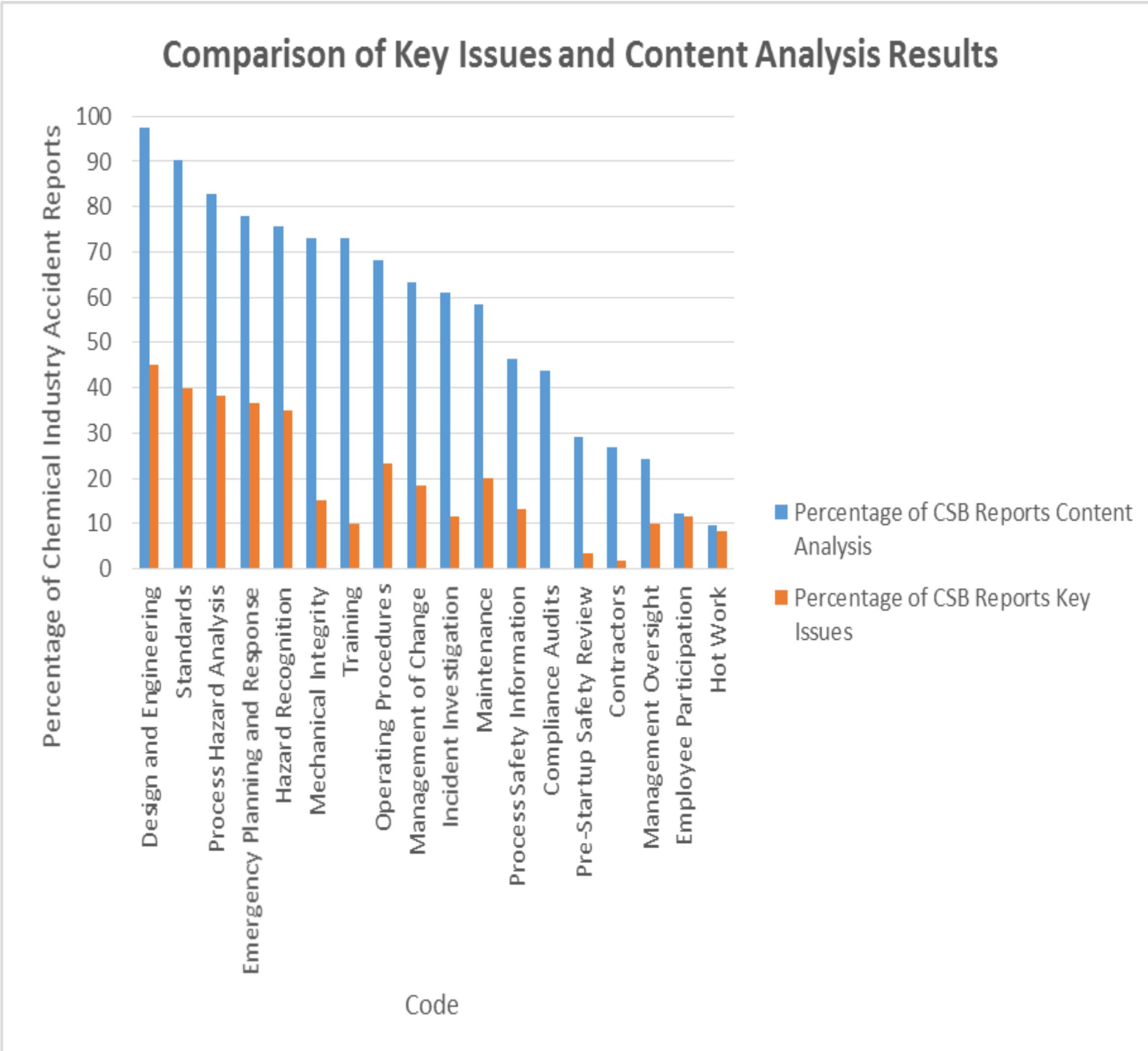


Figure 4.25 | Comparison of Key Issues and Content Analysis Results

Looking at the comparative results, several codes occurred with high frequency both in the Key Issues analysis (Key Issues collected by the accident investigator and report writer, discussed in Section 4.2) and the content analysis just described in Section 4.3. These include: emergency planning and response, design and engineering, hazard recognition, process hazards analysis, and standards. The agreement of the two analyses in these top areas indicates that these are most likely important factors in chemical industry accidents.

Emergency planning and response occurred in 37% of chemical industry accident reports studied as an identified Key Issue, and 78% identified during the content analysis. The top emergency planning issues included a lack of an emergency plan, a lack of drills, and a lack of involvement from the local community in emergency planning and drilling. The top emergency response issues included the need of assistance from local community responders (insufficient site response capabilities), and communication issues with local emergency responders. These two issues likely contributed to the third emergency response issue: offsite crews injured responding to accident.

Design and engineering occurred in 45% of chemical industry accident reports studied as an identified Key Issue and 98% identified during the content analysis. The most common engineering controls issues included a lack of proper design features to ensure safe operation, materials or equipment design issues, professional participation in the design process, and the system not being installed according to design. The most frequent safety systems issues were a lack of controls followed by a lack of alarm systems or pressure relief valve issues.

Hazard recognition occurred in 35% of chemical industry accident reports studied as an identified Key Issue and 76% identified during the content analysis. The top hazard recognition issues included the employees not being aware of latent hazards and the hazards innate to the design not being understood.

Process hazard analysis occurred in 38% of chemical industry accident reports studied as an identified Key Issue and 83% identified during the content analysis. The most common hazard analysis issues included no hazard assessment performed or an inadequate hazard assessment performed.

Standards occurred in 40% of chemical industry accident reports studied as an identified Key Issue and 90% identified during the content analysis. The most common standards issues were implementation issues with the standards at the facility. Other standards issues included insufficiencies in the standards themselves or their enforcement at the facilities.

These top areas were also frequently associated with each other in the chemical industry accidents studied. Issues with hazard recognition were often strongly associated with design and engineering, and also had ties to hazard assessments. Standards and Design and Engineering were also strongly associated. The emergency planning and response codes were strongly associated with hazard recognition. These associations suggest that improvements in these areas might be impactful not only in the area itself, but in other problem areas as well.

Some areas, such as training, operating procedures, and mechanical integrity, among others, were much more prevalent in the detailed content analysis, 73%, 68%, and 73%, respectively. Prevalence in the content analysis over the Key Issues analysis does not necessarily indicate less of an impact on process safety at a facility, but rather that the investigator and report writer did not pull this issue out as a Key Issue of the accident. In some cases, these were identified root causes, but not Key Issues. The content analysis highlights the areas that warranted mention in the text of the reports and the frequencies of even the top 5 themes in the Key Issues analysis were much higher in the content analysis.

The two analyses presented in this chapter, the Key Issues analysis and the content analysis provide the data that are used in Chapter 6 of this study to develop theories to improve safety and efficiency of operations at nuclear chemical facilities, and subsequent performance measures to monitor performance in these areas.

CHAPTER 5

NUCLEAR CHEMICAL FACILITY ACCIDENT ANALYSIS

5.1. Introduction

Nuclear chemical facilities combine the hazards of radioactive materials with complex chemical operations. Because the nuclear and chemical industries use distinct approaches to safety management, chemical hazards, which are commonly addressed in the chemical industry, may receive less coverage in nuclear facilities where radiological hazards have been the predominant focus.

The goal of Chapter 5 is to identify the common causes and themes of occurrences in nuclear chemical facilities. This is divided into three objectives, to describe the content analysis of DOE occurrence reports, to describe the content analysis of NRC abnormal occurrence reports, and to provide a comparison of these results to highlight the most important causes and themes.

This chapter presents a content analysis of accident reports at nuclear chemical facilities (DOE Occurrence and Reporting System Reports and NRC Abnormal Occurrence Reports to Congress) using a coding structure focused on chemical hazards derived from the content analysis in Chapter 4. This content analysis yields data that can be used to improve process safety management at these facilities, and highlights areas from the chemical industry accident analysis that are particularly important at nuclear chemical facilities. The occurrence reports contain potential trend information that can be used to determine lessons learned in the nuclear industry that could be applied to nuclear chemical facilities to improve process safety. There were 47 occurrence reports included from the DOE database in this analysis. Only four reports about nuclear chemical facilities were included in the NRC's abnormal occurrences report to congress between the years 1998 and 2012.

The outline of Chapter Five is as follows:

5.2 Content Analysis of the DOE Occurrence Reports
5.3 Content Analysis of the NRC Abnormal Occurrence Reports
5.4 Overall Results from Nuclear Chemical Facilities

5.2. Content Analysis of the DOE Occurrence Reports

The following sections describe the content analysis of the select DOE Occurrence Reports from Nuclear Chemical facilities.

5.2.1. Introduction

The Department of Energy (DOE) has recently expanded the number of nuclear chemical facilities associated with its waste management mission. There are a number of facilities already in operation, such as the plants for processing depleted uranium hexafluoride at Portsmouth and Paducah and the actinide removal process/ modular caustic side solvent solution (ARP/MCU) at Savannah River. While these facilities process radiological material, and thus must contend with the hazards of a typical nuclear facility, there is a key difference in their operating hazards from other types of facilities: complex chemical operations. In many cases, the process flow diagram for these nuclear chemical facilities more closely resembles a complex chemical operation than a nuclear reactor facility. The current approach for safety management at these nuclear chemical facilities is rooted in nuclear industry hazards analysis techniques and could benefit from lessons learned particular to chemical operations at nuclear chemical facilities. This research mined the data available in the DOE Occurrence Reporting and Processing System (ORPS) through content analysis in order to extract themes and trends in occurrences at nuclear chemical facilities.

Discussed in detail in Chapter 2, the DOE's safety management processes are focused on preventing accidents from occurring. However, if there is an occurrence, the DOE turns to the accident investigation process described in DOE Order 225.1B (DOE, 2011e) and the subsequent causal analysis through Order 232.2 (DOE, 2011c) to identify lessons to be learned. In general, the number of accident investigations is few compared to the number of occurrence reports. Accident investigations are also documented in occurrence reports, making the ORPS database an ideal database for the analysis.

DOE Order 225.1B defines the process for accident investigation of DOE occurrences. The first step in the investigation process is to appoint the Accident Investigation Board, which consists of a chairperson and 5-6 members, all DOE Federal employees with subject matter expertise and knowledge of DOE's ISM program. During the investigation process, the AIB will examine the accident scene, investigate interested and/or impacted individuals, organizations, management systems or facilities, examine DOE and contractor documentation, interview witnesses or personnel associated with the accident and perform engineering tests and analyses as appropriate. From these data sources, the AIB will derive causal factors (direct, root and contributing causes) associated with human performance and safety management systems which will be used to support the development of an accident investigation report. In closing out the investigation, lessons learned will be formally distributed, and corrective actions must be approved, completed and implemented.

The current framework for eliciting feedback provided by incident reporting, evaluation and analysis at DOE nuclear facilities is one in which the DOE utilizes a systematic, detailed occurrence analysis categorization process (documented in DOE Order 232.2, Occurrence Reporting and Processing of Operations Information and Standard 1197-2011, Occurrence Reporting Causal Analysis) (DOE, 2011b; DOE, 2011c); the categorization process was informed by the practices of the commercial nuclear power industry and the Institute for Nuclear Power Operations (INPO). This process involves the application of a formal Causal Analysis Tree (CAT) with predesigned headings to an accident. Each category is numbered and documented for ease of incident analysis.

The main objectives of DOE O 232.2 are to keep the DOE and National Nuclear Security Administration (NNSA) informed about events that could cause potential negative effects to the health and safety of the public, the workers, the environment, DOE missions, or DOE credibility and to ensure DOE uses organizational learning to enhance mission safety and share effective practices in order to continuously improve process safety and manage process changes.

Reporting under Order 232.2 is required for any occurrence that results from an activity performed by facility personnel; such occurrences must be reported by facility personnel in a timely fashion and investigated and analyzed by facility management as described in the Occurrence Reporting Model, using the cause codes provided in the CAT. This DOE approach to occurrence reporting and categorization is used to write the DOE occurrence reports that will be studied in this analysis.

5.2.2. Methods

The objective of this analysis is to develop an understanding of occurrences at DOE nuclear chemical facilities and their major causes and themes. The methodology for this work involved performing a content analysis of the occurrence reports to identify coherent and important themes using the entire text of the reports and then subdividing the data into categories, patterns and themes, using the methodology described in Chapter 3, and reported in Chapter 4 for chemical industry accident reports. This was completed in a process known as data labeling or indexing which is detailed in the 1996 GAO Guide 10.3.1 (GAO, 1996). During this analysis, content analysis software was again used to allow for automatic text searches and coding. The semi-quantitative data assessment from the content analysis of this research involved studying the occurrence of categories through codes.

For this task, the unit of analysis is one occurrence report from a nuclear chemical facility. The methodology involved the application of a content analysis software for maintenance of coding, document searches and its many other functions.

Previous work described in Chapter 4 involved performing a content analysis of chemical industry accident reports to determine common causes and themes of incidents in the chemical industry. As a part of this analysis, a coding structure was developed based on the OSHA chemical industry standard for Process Safety Management (PSM). In a similar fashion to the nuclear industry, the chemical industry applies a systematic review of chemical processes with emphasis on the following categories: chemical hazards, process technology and equipment, process safety information, employee involvement, process hazard analysis, operating procedures, employee training, contractor requirements and responsibilities, pre-startup safety reviews, hot work permitting, management of change, incident investigation, emergency planning and response, compliance audits, trade secrets, and mechanical integrity. From these categories, and their application to chemical facility process safety, a coding structure was created and applied to the chemical industry accident reports. DOE has accepted the importance of PSM and has promulgated two (2) technical standards (DOE STD 3009 and DOE HDBK 1101-2004) dedicated to its implementation. In order to maintain consistency in coding and better understand the chemical hazards associated with nuclear chemical facilities, and consistent with DOE's stated commitment to PSM, this coding structure based on OSHA PSM review categories formed the basis for coding the occurrence reports in this work as well.

In this analysis, the frequency of codes were studied and associations monitored in the text. Counting the frequency of the codes in the content analysis software simply involved running the program across the different units of analysis and summing total occurrences. Finding associations between the various codes required studying carefully the proximity of wording (or codes) in the report. The content analysis software also allowed for searching various combinations of codes at a given time. This data was also evaluated by analyzing frequency of occurrence. For instance, if a code related to chemical leakage was often followed by a code related to fires, the instances of fires after chemical leaks might be an important result from the data. This process is more thoroughly described in Chapter 3.

Figure 5.1 contains the generic coding structure for the content analysis. The more detailed description of the codes and memos applied to the text is contained in Chapter 4.

Codes	
	Compliance Audits
	Contractors
	Emergency Planning and Response
	Employee Participation
	Design and Engineering
	Hazard Recognition
	Hot Work
	Incident Investigation
	Maintenance
	Management of Change
	Management Oversight
	Mechanical Integrity
	Operating Procedures
	Process Hazard Analysis
	Pre-Startup Safety Review
	Process Safety Information
	Standards
	Training

Figure 5.1 | Generic Coding Structure for the Content Analysis

5.2.3. Results

In total, 47 DOE occurrence reports from the ORPS database were analyzed including occurrences between 1998 and 2012 at the Defense Waste Processing Facility (DWPF) and Actinide Removal Process/ Modular Caustic Side Solvent Extraction Unit (ARP/MCU) at SRS, the LosAlamosTA-55 Facility, the Uranium Hexafluoride Conversion Plants at Portsmouth and Paducah, and the Hanford high level waste treatment facilities. The overall results of the content analysis of the DOE ORPS reports are illustrated in Figure 5.2. The results are reported as the percentage of DOE ORPS reports that contained codes from each category listed.

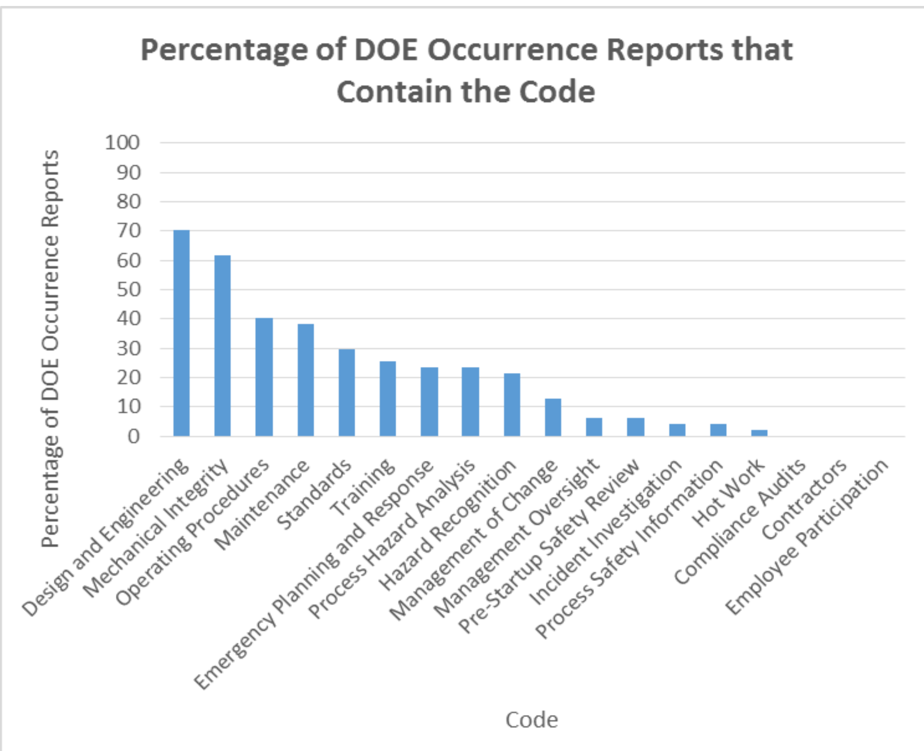


Figure 5.2 | Percentage of DOE Occurrence Reports that Contain each Code

Due to the transition from chemical industry reporting (solely PSM based) to nuclear industry reporting (DOE or NRC guidelines), some codes were not discussed in the occurrence reports, such as compliance audits or contractor issues, among others. This does not imply that there are or are not contractor and/or audit issues involved in the occurrences, but these topics were not covered in the text of DOE occurrence reports. However, contractors play an integral role in performing the work at DOE facilities.

Further, several codes that were prevalent in many of the DOE ORPS reports, such as Design and Engineering (70% of the studied ORPS reports) and Mechanical Integrity (62% of the studied ORPS reports), were also important in the chemical industry accident reports, indicating their overall value to operations at nuclear chemical facilities.

A more detailed examination of the results for the top occurring DOE issues (occurring in more than ¼ or 25% of the analyzed occurrence reports) follows in sections 5.2.3.1- 5.2.3.6.

5.2.3.1. Content Analysis Results for Design and Engineering

Design and Engineering codes were the most prevalent codes in the DOE Occurrence Reports, occurring in 70% of the analyzed occurrences. These codes were broken down by engineering controls and safety systems.

5.2.3.1.1. Content Analysis Results for Engineering Controls

The engineering controls code appeared in 21% of the studied DOE nuclear chemical facility occurrence reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 5.3.

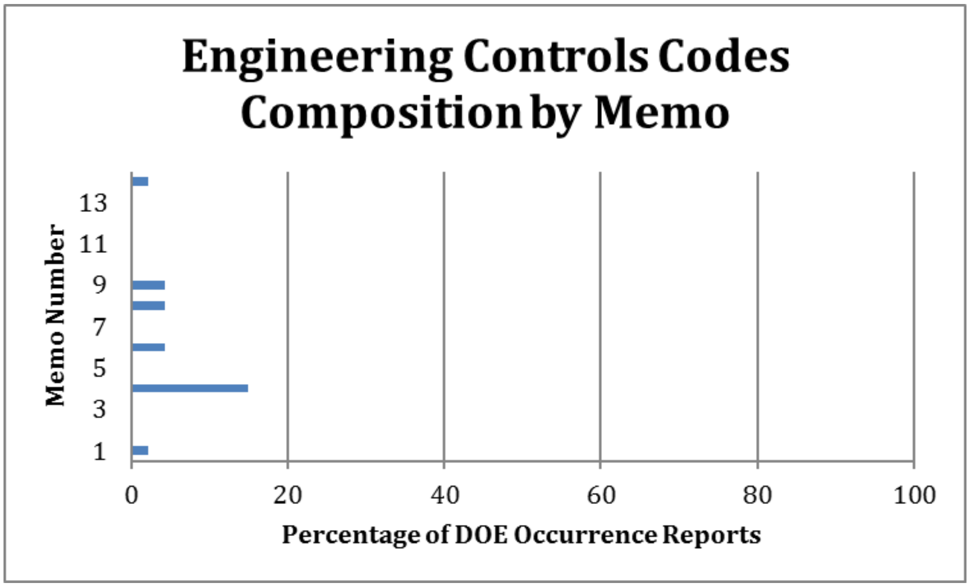


Figure 5.3 | Engineering Controls Code and Associated Memos

The memos for engineering controls illustrated in Figure 5.3 demonstrate that the DOE occurrence engineering controls issues were diverse. However, clearly the most common issue associated with engineering controls codes was EC4- Materials or equipment design issues in 15% of the studied occurrences. EC6- Design drawings or information not complete, EC8- Design hazard recognition and EC9- System not installed according to design or other requirements were also prevalent, though they only occurred in 4.5% of the studied occurrences.

Associations with engineering control codes were related to hazard recognition and mechanical integrity.

5.2.3.1.2. Content Analysis Results for Safety Systems

The safety systems code occurred in 57% of the studied DOE nuclear chemical facility occurrence reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 5.4.

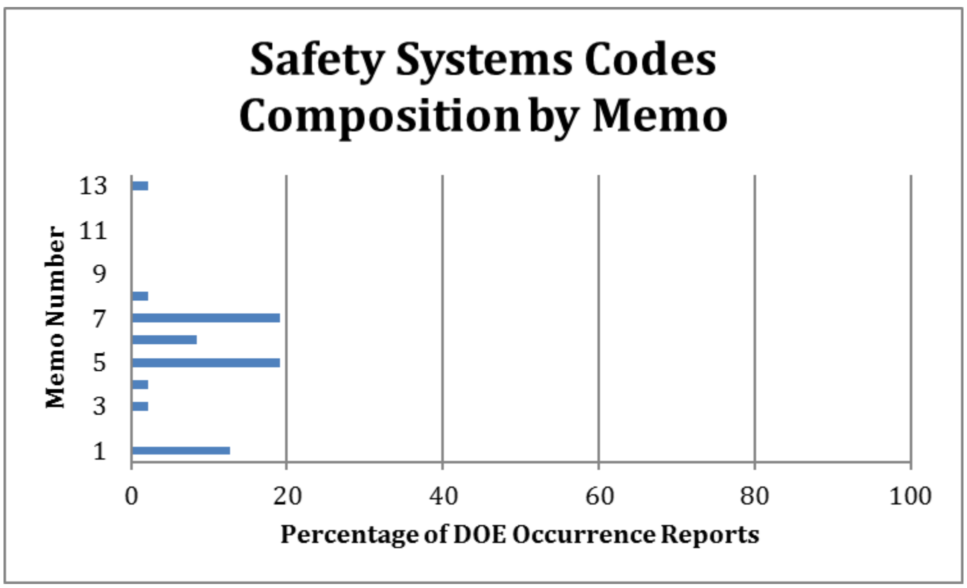


Figure 5.4 | Safety Systems Code and Associated Memos

SS5- Lack of controls (layers of protection) and SS7- Reliability of safety controls occurred in 19% of the studied DOE nuclear chemical facility occurrences. These issues are both indicative of issues in these instances relating to the DOE safety management system. In the design of systems and through the completion of hazards analysis, sufficient layers of protection should be identified and their reliability studied. These codes are accompanied by SS1- Failure to wear PPE which occurred in 13% of the studied occurrences. In some cases, this issue was related to a lack of appropriate PPE for the hazards, an issue with job planning.

Associations with safety systems codes were hazard recognition, hazards analysis, and training.

5.2.3.2. Content Analysis Results for Operations and Maintenance

The following sections contain the results for the content analysis of DOE ORPS in the areas of Operations and Maintenance.

5.2.3.2.1. Content Analysis Results for Maintenance

The maintenance code occurred in 38% of the studied DOE nuclear chemical facility occurrence reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 5.5.

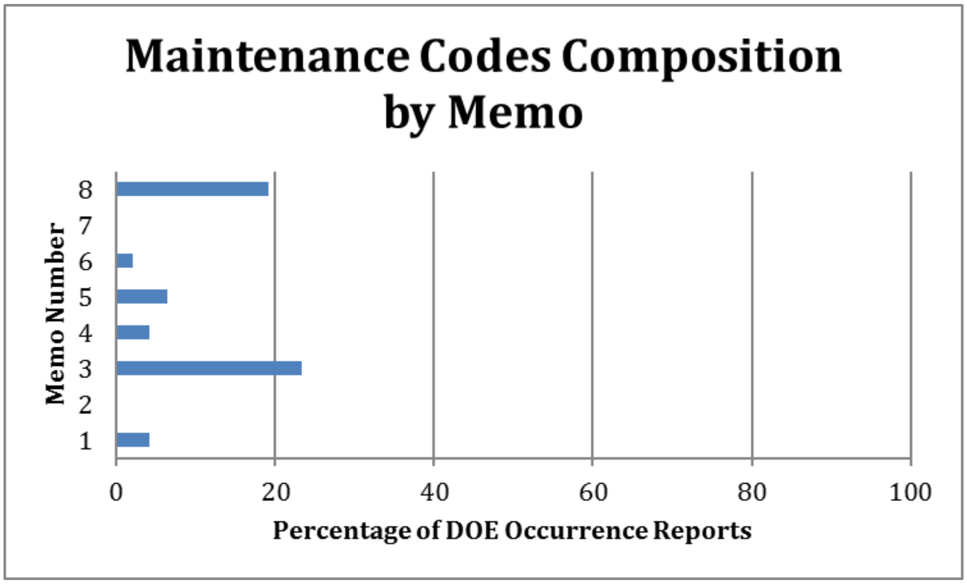


Figure 5.5 | Maintenance Code and Associated Memos

Issues in maintenance were most strongly related to MA3- Maintenance plan is LTA in 23% of the studied nuclear chemical facility occurrences, and MA8- Endangerment of maintenance workers in 19% of the studied occurrences. The most common issue was a less than adequate plan to accomplish maintenance. This LTA work planning may have also had an effect on the endangerment of maintenance workers metric, putting workers in less than ideal safety situation.

Common associations with maintenance codes were hazard recognition, operating procedures, and mechanical integrity.

5.2.3.2.2. Content Analysis Results for Mechanical Integrity

The mechanical integrity code occurred in 29% of the studied DOE nuclear chemical facility occurrence reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 5.6.

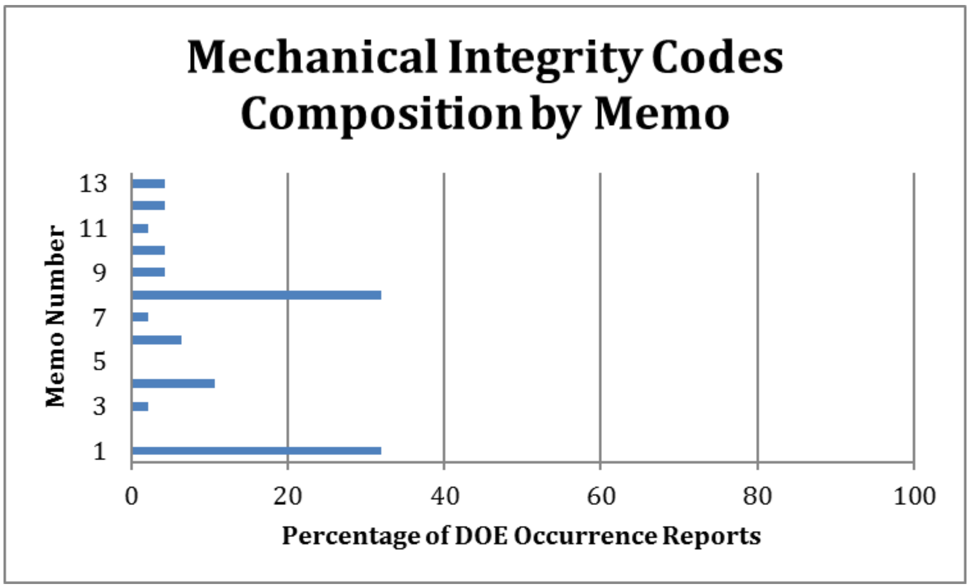


Figure 5.6 | Mechanical Integrity Code and Associated Memos

The two most common issues, MI1- Inoperable equipment and MI8- Corrosion or degradation of materials both occurred in 32% of the studied DOE nuclear chemical facility occurrences. These two issues were indicative of a problem discussed often during conversations with DOE subject matter experts of the aging infrastructure and degradation of equipment and materials installed during the 1950s and 1960s, which has reached the end of, or exceeded in some cases, its recommended life cycle (Omnibus Risk Review Committee, 2015). MI4- Inspections and tests performed after the fact occurred in 11% of the studied occurrences. This issue referred to an inspection which was likely to have turned up an issue occurring too late, once the occurrence had happened.

Common associations with mechanical integrity issues include hazards analysis and maintenance.

5.2.3.2.3. Content Analysis Results for Operating Procedures

The operating procedures code occurred in 40% of the studied DOE nuclear chemical facility occurrence reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 5.7.

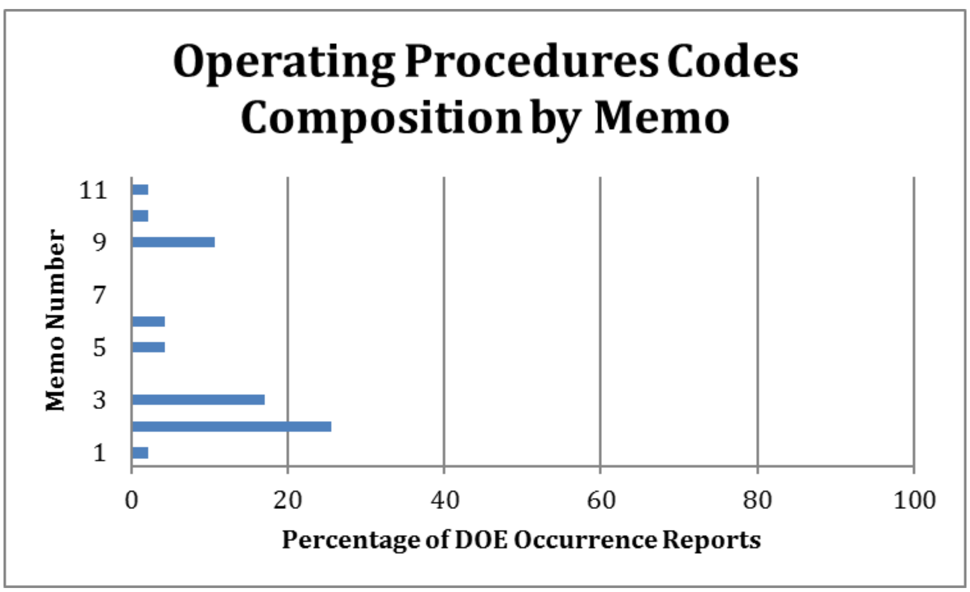


Figure 5.7 | Operating Procedure Code and Associated Memos

Two main issues were highlighted in the operating procedures category of analysis. OP2- Procedure does not contain clear instructions for a part of the process occurred in 26% of the studied DOE nuclear chemical facility occurrences. This issue highlighted the need for thorough operating procedures that are maintained current with the operating conditions of the system. OP3- Procedure not followed by operators in 17% of the occurrence reports also highlighted the need for current and accurate procedures, so that operators would follow them as necessary to ensure safe and consistent operations. OP9- Revisions to operating procedures occurred in 11% of the studied chemical industry accidents and reiterated the need for revisions to operating procedures to keep them up to date.

Associations with operating procedures included process safety information, management of change, and training.

5.2.3.3. Content Analysis Results for Standards

The standards code occurred in 30% of the studied DOE nuclear chemical facility occurrence reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 5.8. Only one area of standards codes was represented in the DOE ORPS reports, facility implementation.

5.2.3.3.1. Content Analysis Results for Standards Facility Implementation

The following Figure 5.8 illustrates the Standards-Facility Implementation Code and Associated Memos.

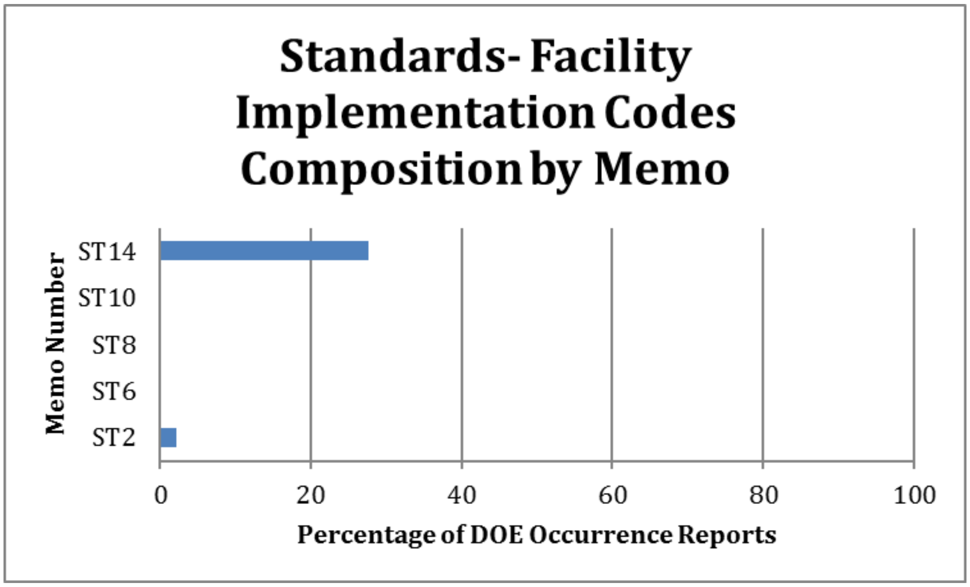


Figure 5.8 | Standards-Facility Implementation Code and Associated Memos

Only two standards issues occurred in the DOE occurrence reports, which is indicative of the highly regulated environment under which these facilities operate. The standards codes included ST14- Standard compliance which occurred in 28% of the occurrence report, a large portion of the total 30% of standards issues coded. This code indicated that the facility may have been out of compliance with a standard. ST2- the only other standards issue coded occurred in 2% of the studied occurrences.

There were no noteworthy associations for the standards codes in the DOE occurrence reports.

5.2.3.4. Content Analysis Results for Human Factors

The following sections contain the results from the content analysis of the DOE ORPS with respect to the Human Factors codes.

5.2.3.4.1. Content Analysis Results for Training

The training code occurred in a little over a quarter, or 26%, of the studied DOE nuclear chemical facility occurrence reports. These codes were further broken down into issues using the memos described in the methodology as follows in the chart in Figure 5.9.

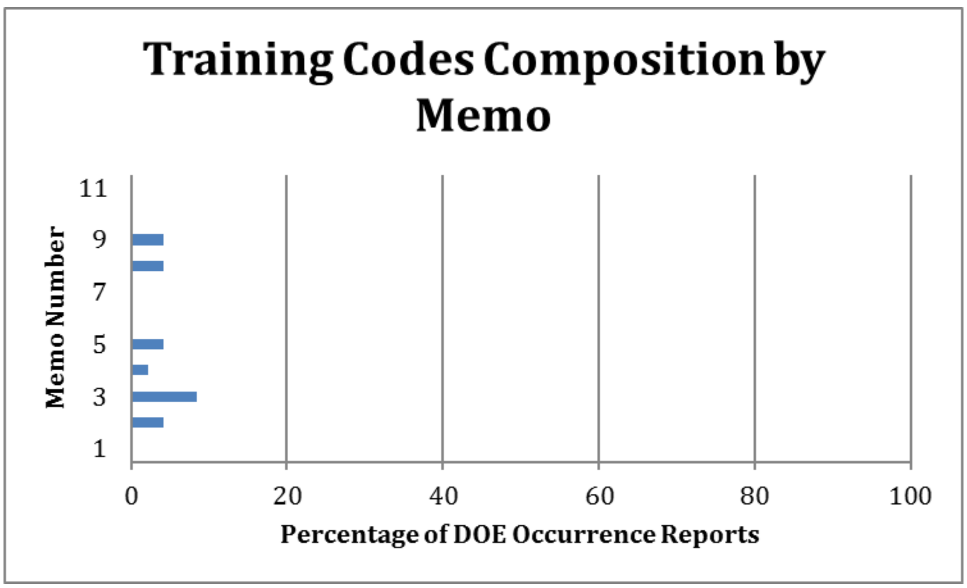


Figure 5.9 | Training Code and Associated Memos

Training issues in the DOE nuclear chemical facility occurrence reports were fairly evenly divided, and no single issue occurred in more than 10% of the studied occurrences. One memo, TR3- Refresher training provided for hazards occurred in 9% of the occurrences and was thus the most likely issue to be carried forward from this analysis. This memo highlighted the importance of refresher training at nuclear chemical facilities to remind the operators and maintenance technicians about the hazards involved in the process.

Associations with training codes were related to hazard recognition. The other training issues involved issues with training planning, ensuring proper information was included, the training was formal and records maintained, and training was thorough.

These results will be combined with insights from the NRC Abnormal Occurrence results described in Section 5.3, and used to develop a tool to compare chemical industry accident issues against those of nuclear chemical facilities. The comparison is described in Chapter 6.

5.3. Content Analysis of the NRC Abnormal Occurrence Reports

The following sections describe the content analysis of the NRC Abnormal Occurrence Reports to Congress.

5.3.1. Introduction

Another source of information about occurrences at nuclear chemical facilities was four abnormal occurrence reports provided to Congress by the NRC between 1998 and 2012. These reports, which detail information about occurrences at NRC licensees and occurrences at their nuclear chemical facilities were also used to perform a content analysis. The abnormal occurrences were analyzed using the same content analysis procedure described in section 5.2.2, above. More information about the NRC abnormal occurrence reporting process and the abnormal occurrence reports can be found in Chapters 2 and 3 of this study. Due to the small number of abnormal occurrences reported during the given time period at nuclear chemical facilities, this analysis provides only a resource to verify that information from the other analyses would apply to nuclear chemical facilities.

5.3.2. Methodology

The objective of this analysis was to develop an understanding of abnormal occurrences at NRC licensed nuclear chemical facilities and their major causes and themes. Similarly to the analysis of DOE Occurrence Reports, the methodology for this work involved performing a content analysis of the abnormal occurrence reports to identify coherent and important themes using the entire text of the reports and then subdividing the data into categories, patterns and themes, in the same way described in Chapter 3, and reported in Chapter 4 for chemical industry accident reports.

The same coding structure was applied to the NRC abnormal occurrences, and the frequencies of codes and memos in the text were studied to identify key themes and issues in abnormal occurrences at commercial nuclear chemical facilities. The more detailed description of the codes and memos applied to the text is contained in Section 5.2.2, and Chapter 4, for reference.

5.3.3. Results

The following sections contain the results from the content analysis of NRC abnormal occurrence reports at nuclear chemical facilities. Only four reports about nuclear chemical facilities were included in the NRC's abnormal occurrences report to congress between the years 1998 and 2012. Due to the small number of reports analyzed, the percentages only mark which issues were prevalent, and should not be taken to indicate a representative issue with a high frequency of occurrences at commercial nuclear chemical facilities as a whole.

The overall results of the content analysis of the NRC Abnormal Occurrence reports are illustrated in Figure 5.10. The results are reported as the percentage of NRC Abnormal Occurrence reports that contained codes from each category listed.

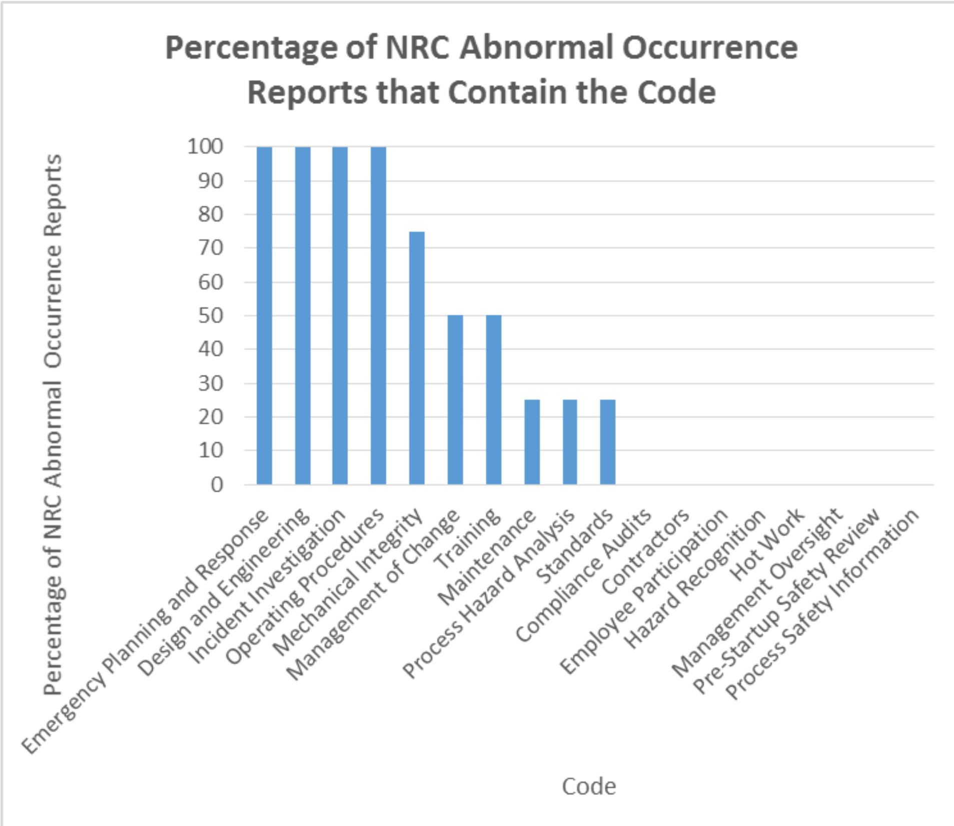


Figure 5.10 | Percentage of NRC Abnormal Occurrence Reports for Each Code

According to Figure 5.10, there are 6 codes which occurred in more than 2 of the studied NRC abnormal occurrence reports: Emergency planning and response, design and engineering, incident investigation, management of change, mechanical integrity, and operating procedures.

It was not worthwhile to include full details of all the memos associated with each code, but the following memos for each category listed in Table 5-1 were identified during the content analysis of NRC abnormal occurrence reports.

Table 5-1 | Memos Appearing in NRC Abnormal Occurrence Reports

Code	**Memos**
Engineering Controls	EC1- System does not contain design features necessary for safe operation EC2- Physical failure due to underdesign EC3- Failure to control equipment
Safety Systems	SS1- Failure to wear PPE SS2- Lack of remote equipment for process safety SS3- Ventilation system insufficient SS4- Failure of a backup safety system (cooling) SS5- Lack of controls (layers of protection) SS6- Lack of alarm system
Emergency Planning	EPP1a- Lack of emergency plan EPP3a- Failure to account for all personnel EPP3b- Failure to sound alarm system EPP3c- Community and other responders aware of and involved in emergency planning EPP3d- Failure to follow plan
Emergency Response	ERR1- Failure to establish safety of environment at facility ERR2- Offsite responders participate in drills ERR3- Site information shared with emergency responders ERR4- Community evacuation issues ERR5- Communication issues with local emergency response
Incident Investigation	II1- Previous accidents were ignored II2- Lessons learned applied to new situations
Maintenance	MA-1: Maintenance not alerted of issue
Mechanical Integrity	MI1- Inoperable equipment MI2- Lack of preventative maintenance program MI3- Equipment issues caused by accident worsened accident conditions MI4- Inspections and tests performed after the fact

	MI5- No MI procedures in place
Management of Change	MOC1: Shift turnover changes MOC2- Reconfiguration without instructions
Operating Procedures	OP1- Inadvertent addition of material not in procedure OP2- Procedure does not contain clear instructions for a part of the process OP3- Procedure not followed by operators OP4- Procedures rely on memory of facility workers and are not written OP5- No procedure for abnormal conditions
Process Hazards Analysis	PHA1- Risks associated with the process not well analyzed
Standards	ST1- Guidance for review of facility is insufficient
Training	TR1- Employees not trained in use of maintenance requests or maintenance TR2- Training lacks process safety information (use of cautions and warnings, equipment purposes etc)

5.4. Overall Results from Nuclear Chemical Facilities

The overall results from the analysis of DOE nuclear chemical facility occurrence reports and NRC abnormal occurrence reports are compared in Figure 5.11. The percentage of NRC reports should again be approached with caution due to the very small number of reports from commercial nuclear chemical facilities that are included in the analysis.

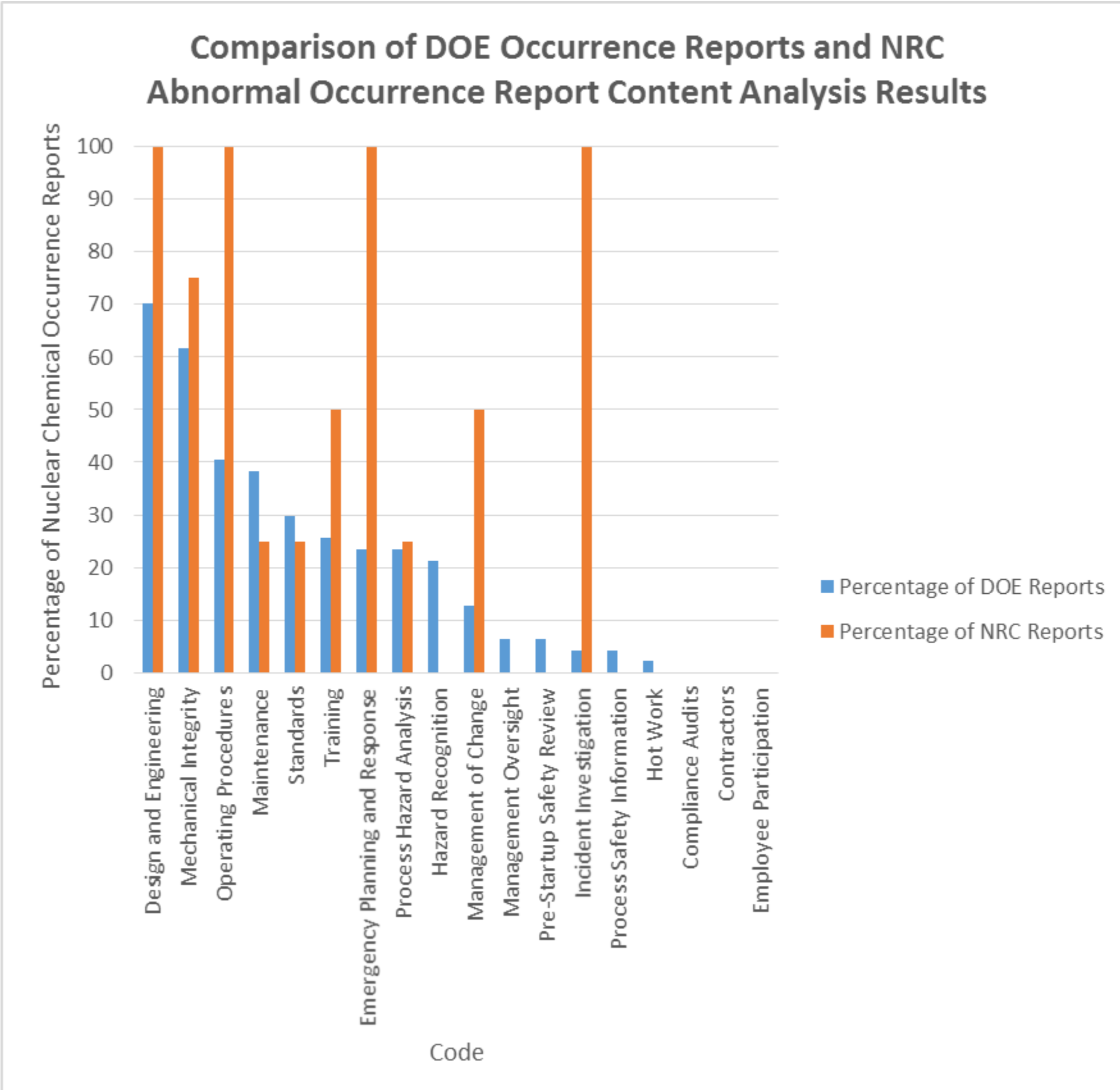


Figure 5.11 | Comparison of DOE and NRC Nuclear Chemical Facility Occurrence Report Content Analysis Results

Figure 5.11 illustrates the areas which were mutually important issues in the DOE and NRC occurrences at nuclear chemical facilities. Looking at the comparison, several codes were important factors in all studied occurrences at nuclear chemical facilities, including design and engineering, maintenance, mechanical integrity, and operating procedures. Although the DOE Occurrences covered a broader set of occurrences, the spikes for DOE occurrence reports coincide with the presence of many of the issues at NRC commercial nuclear chemical facilities as well, with the exception of incident investigation which is less prevalent in the content of DOE occurrence reports, but appeared in all 4 of the studied NRC accidents; this is not surprising, as the bar for what constitutes an Abnormal Occurrence for NRC fuel cycle and materials licensees is fairly high and normally involves site-wide impacts.

The two analyses presented in this chapter, the content analysis of DOE nuclear chemical facility ORPS reports and NRC nuclear chemical facility abnormal occurrence reports provided data comparable to that developed in Chapter 4 for chemical facilities, to ensure that chemical facility data was representative of nuclear chemical facilities, which are targeted by this study. This data is used comparatively in Chapter 6 to develop theories to improve safety and efficiency of operations at nuclear chemical facilities, and subsequent performance measures to monitor performance in these areas.

CHAPTER 6

DEVELOPMENT OF THEORY AND PERFORMANCE MEASURES

6.1. Introduction

The data from Chapters 4 and 5 was analyzed with the goal to develop theories about safety and efficiency of operations. The goal of Chapter 6 is to detail the process involved in taking the results and translating them into theories about the safety and operation of nuclear chemical facilities and to postulate a set of performance measures for nuclear chemical facilities that utilize knowledge from the chemical industry and currently operational nuclear chemical facilities. The objectives of this chapter are to provide an overview of the results from Chapters 4 and 5 highlighting the most important issues, to describe the development of theories about safety and efficiency of operations at nuclear chemical facilities, to describe the development of leading performance indicators to monitor these theories, and to describe the process of subject matter elicitation used to select the most impactful of these performance measures.

The translation from data to theory to performance measures is described in this chapter, as well as the process of subject matter expert review of the performance measures. The focus of this subject matter expert elicitation was to ensure the performance measures recommended for use at nuclear chemical facilities are both practical, meaning that they could be measured, and effective, meaning that their measurement and subsequent tracking would provide usable information about the status of safety at the facility. The resulting recommended performance measures are presented at the end of this chapter for application to nuclear chemical facilities.

The process of development and selection of practical and effective performance measures is outlined in Chapter 6 as follows:

6.2 Comparing the Results from Chemical Industry and Nuclear Chemical Facility Analyses

6.3 Development of Theory

6.4 Performance Measure Development

6.5 Expert Review of Performance Measures

6.6 Final Proposed Performance Measures.

6.2. Comparing the Results from Chemical Industry and Nuclear Chemical Facility Analyses

Chapters 4 and 5 detail the results of the analyses of the chemical industry accident reports and occurrences at nuclear chemical facilities, respectively. The analyses of the chemical industry accident reports and nuclear chemical facilities demonstrated that there were similar issues involved in incidents at both types of facilities. The similarities between the analyses are described in the graph and subsequent text below. These similarities indicated areas and issues that were consistently present in accidents in the chemical industry and occurrences at the analyzed nuclear chemical facilities. This presence in accidents and occurrences was theorized to indicate that improvement and/or monitoring of these areas would increase safety and efficiency of operations at nuclear chemical facilities. The following chart in Figure 6.1 illustrates the overall results from the analyses.

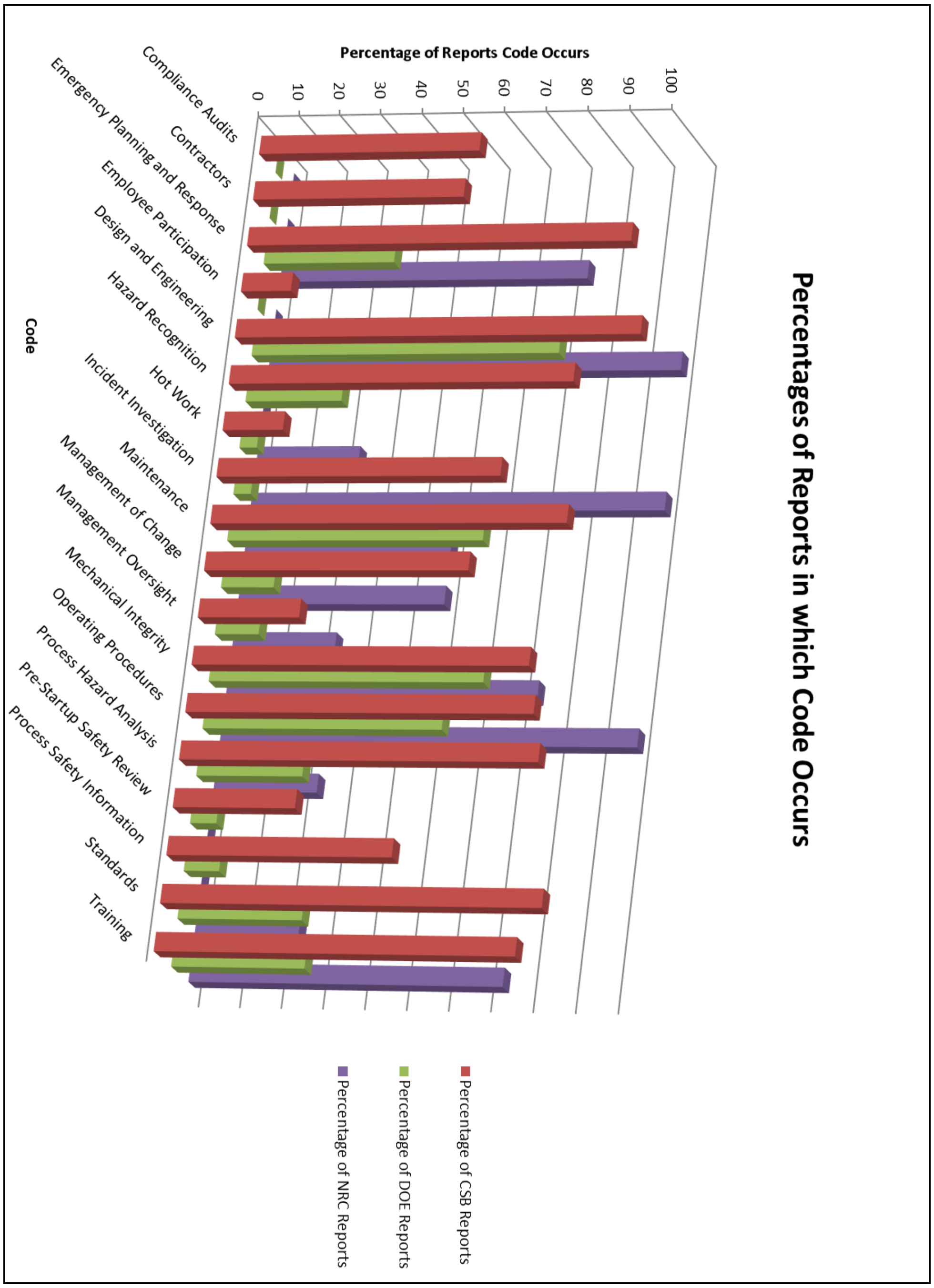


Figure 6.1 | Percentage of all Reports in which Code Appears

Figure 6.1 indicates areas of importance that were used to develop theories about safety and efficiency and subsequent performance measures. These top occurrence codes include design and engineering, both engineering controls and safety systems; operating procedures; maintenance; mechanical integrity; hazards analysis; incident investigation; and emergency planning and response.

The most important memos from the chemical industry accident analysis, which were also shown to be important by the analysis of nuclear chemical facility occurrences are listed below.

Design and Engineering:

1. EC1- System does not contain design features necessary for safe operation
2. EC4- Materials or equipment design issues
3. EC9- System not installed according to design or other requirements
4. EC10- Engineers or professionals participation in design process and knowledge of design standards
5. SS5- Lack of controls and layers of protection
6. SS6- Failure of or lack of alarm system
7. SS9- Failure of or lack of pressure relief devices

Operating Procedures:

1. OP2- Procedure does not contain clear instructions for a part of the process (outdated or incomplete)
2. OP3- Procedure not followed by operators
3. OP5- No procedure for abnormal conditions
4. OP6- Procedure does not contain PSI

Maintenance:

1. MA3- Maintenance plan is LTA
2. MA4- Performance of maintenance LTA

Mechanical Integrity:

1. MI5- No MI procedures in place
2. MI6- Equipment repeatedly causes issues
3. MI8- Corrosion or degradation of materials
4. MI10- Deficiencies corrected in timely manner

Hazards Analysis:

1. PHA1- Risks associated with the process not well analyzed by team members
2. PHA2- PHA inadequate- i.e. acceptance of lower tier safety controls
3. PHA4- PHA results not used or updated
4. PHA7- No PHA performed

Incident Investigation:

1. II1- Precursor accidents were ignored
2. II2- Lessons learned not applied to new situations in a timely manner, or at all
3. II3- No actions taken or tracked based on investigation of previous events

Emergency Planning and Response:

1. EPP1- Lack of emergency plan
2. ERR5- Communication issues with local emergency response
3. ERR6- Assistance necessary from additional local emergency crews that are untrained
4. ERR8- Offsite crews injured due to inexperience with hazards or attempting to rescue others without planning

5. ERT1- Emergency response crews participate in training with real drills and process information

6.3. Development of Theory

Section 6.3 describes the methods and results for the development of theory based on the issues determined during the content analysis.

6.3.1. Introduction

Once the iterative content analysis was completed, and the results compiled for chemical industry accidents and nuclear chemical facility occurrences, the next step was to consider what theories could be developed based on this data to improve safety and efficiency of operations at a nuclear chemical facility. This process was completed using the Grounded Theory development processes described in Chapter 3 to translate the issues into theories about safety and efficiency of operations at nuclear chemical facilities.

6.3.2. Methods

The following steps summarize the process used in this study for theory development (a more detailed description of the concepts of Grounded Theory can be found in Chapter 3):

- Start with the qualitative data

- Review the data collected
- Repeated ideas, concepts or elements become apparent, and are tagged with *codes*, which have been extracted from the data
- As more data is collected, and as data is re-reviewed, codes can be grouped into concepts, and then into categories
- These categories may become the basis for a theory

Once the data in Chapters 4 and 5 was finalized and occurrences of memos, codes, and categories tallied and compiled, the basis for theories about safety of operations at nuclear chemical facilities was established. In the following results section, theories discussed were developed for each of these categories and the highest frequency issues.

6.3.3. Results

The results for theory development are presented below. For each category, there is a section containing the Issue followed by the Theory. Each Issue and Theory is numbered for reference.

6.3.3.1. Engineering Theories

Issue 1: System does not contain design features necessary for safe operation. [EC1]
Theory 1: Ensuring the application of industry standards or best practices in design will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 2: Materials or equipment have design issues which exacerbated or caused an accident or occurrences. [EC4]
Theory 2: Ensuring the application of industry standards or best practices in material selection and equipment design will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 3: The system was not installed in accordance with design or other requirements, and therefore did not function as designed. [EC9]
Theory 3: Ensuring that the design is followed during the installation of the facility, and checking to ensure it meets specifications will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 4: Lack of adequate participation from engineers and design experts in performing design calculations and developing the process design [EC10]
Theory 4: Ensuring adequate participation from engineers and design experts in performing design calculations and developing the process design will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 5: Insufficient system controls and/or layers of protection resulted either exacerbated or caused an accident to occur. [SS5]
Theory 5: Ensuring the system has been reviewed for safety and the hazards analysis process has tied safety systems to hazards where necessary will improve safety and efficiency of operation at nuclear chemical facilities.

Issue 6: Either the lack of an alarm system or the failure of an existing alarm system worsened the outcome of an occurrence. [SS6]

Theory 6: Ensuring the existence and functionality of alarm systems, including their transmission in all locations of the facility will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 7: Either the lack of a pressure relief device, or the failure of such a device resulted in the occurrence, or worsened the outcome of the occurrence. [SS9]

Theory 7: Ensuring the proper maintenance and application of pressure relief devices and safety systems in general will improve safety and efficiency of operations at nuclear chemical facilities.

6.3.3.2. Operating Procedures Theories

Issue 8: The procedure does not contain clear instructions for a part of the process, it is either outdated or incomplete and this resulted in an error that caused an occurrence. [OP2]

Theory 8: Ensuring that procedures are up to date and cover the process step by step will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 9: The procedure was not followed by operators, causing a misstep that resulted in an occurrence. [OP3]

Theory 9: If operators follow procedures step by step, this action will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 10: There was no procedure in place for abnormal operating conditions, such as higher temperature or pressure than anticipated. [OP5]
Theory 10: If procedures are written to anticipate and provide instructions for abnormal operating conditions, it will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 11: The procedures did not contains process safety information that would have aided operators in making decisions about the operations of the system. [OP6]
Theory 11: If operating procedures contain process safety information, it will improve safety and efficiency of operations at nuclear chemical facilities.

6.3.3.3. Maintenance Theories

Issue 12: Maintenance planning is less than adequate, resulting in dangerous or abnormal conditions at the facility. [MA3]
Theory 12: Adequate maintenance planning will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 13: The performance of maintenance tasks is less than adequate, resulting in an occurrence at the facility. [MA4]
Theory 13: Ensuring maintenance tasks are carried out as planned will improve safety and efficiency of operations at nuclear chemical facilities.

6.3.3.4. Mechanical Integrity Theories

Issue 14: There were no procedures for the completion of mechanical integrity requirements, such as inspections or tests in place, leading to degraded operating conditions at the facility. [MI5]

Theory 14: Ensuring mechanical integrity procedures are in place will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 15: A piece of equipment at the facility repeatedly causes issues, but nothing is done to resolve the problem, resulting in an issue or occurrence. [MI6]

Theory 15: Ensuring the mechanical integrity of all systems will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 16: There is corrosion or degradation of materials at the facility that results in a problem or occurrence. [MI8]

Theory 16: Ensuring mechanical integrity programs monitor and correct corrosion and degradation problems in a timely manner will improve safety and efficiency of operations at a nuclear chemical facility.

Issue 17: Deficiencies are identified at the facility, but not corrected in a timely manner resulting in degraded safety conditions. [MI10]

Theory 17: Ensuring timely correction of deficiencies will improve safety and efficiency of operations at nuclear chemical facilities.

6.3.3.5. Hazards Analysis Theories

Issue 18: Risks associated with the process were not well analyzed by team members. [PHA1]

Theory 18: Ensuring that the right subject matter experts are involved in the hazards analysis will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 19: The hazards analysis was inadequate and may have resulted in the acceptance of lower tier safety controls than recommended. [PHA2]

Theory 19: Reviewing the hazards analysis to determine if safety controls are appropriately matched to the hazards will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 20: Hazards analysis results were not used or updated at the facility. [PHA4]

Theory 20: Ensuring timely updates to the hazards analysis after changes have been made to the process will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 21: No hazards analysis was performed on the process involved in the occurrence or accident. [PHA7]

Theory 21: Ensuring hazards analyses are performed on each process will improve safety and efficiency of operations at nuclear chemical facilities.

6.3.3.6. Incident Investigation Theories

Issue 22: Precursor accidents were ignored or not studied. [II1]

Theory 22: Ensuring accident history is studied and occurrences monitored at the facility, including near misses, will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 23: Lessons learned from previous occurrences were not applied to the situations in a timely manner, or at all. [II2]

Theory 23: Ensuring accident history is studied and used to improve existing operations will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 24: No actions were taken based on the investigation of previous events or action resolution was not tracked to ensure implementation. [II3]

Theory 24: Tracking action items to ensure timely resolution will improve safety and efficiency of operations at nuclear chemical facilities.

6.3.3.7. Emergency Planning and Response Theories

Issue 25: There was no plan to handle emergency situations. [EPP1]

Theory 25: Developing and updating a formal emergency plan, as well as ensuring employees are familiar with this plan, will improve safety and efficiency of operations at nuclear chemical facilities.

Issue 26: Communication issues with local emergency responders cause a delay or worsening of accident conditions at the facility. [ERR5]
Theory 26: Training and drilling with local emergency responders will improve safety and efficiency of operations at nuclear chemical facilities, particularly in emergency situations.

Issue 27: Assistance was necessary from additional local emergency crews that are untrained on the facility hazards and layout. [ERR6]
Theory 27: Providing training to local emergency response crews will improve safety and efficiency of operations at nuclear chemical facilities, particularly in emergency situations.

Issue 28: Offsite crews are injured due to inexperience with hazards or attempting to rescue others without planning. [ERR8]
Theory 28: Training offsite crews and communicating with them in advance will improve safety and efficiency of operations at nuclear chemical facilities, particularly in emergency situations.

Issue 29: Lack of training and lack of resources for emergency responders, leaving them unsure of the hazards and not able to provide the most efficient assistance to the facility [ERT1]
Theory 29: Providing training to offsite emergency responders on the facility hazards and response protocols will improve safety and efficiency of operations at nuclear chemical facilities.

6.4. Performance Measure Development

The following sections in 6.4 describe the process of taking the theories developed in 6.3 and translating them into performance measures, as well as the performance measures, themselves.

6.4.1. Introduction and Overview

The theories developed in the previous section were used to postulate a set of performance measures for nuclear chemical facilities that utilize knowledge from the chemical industry and currently operational nuclear chemical facilities. Each proposed performance measure was tied to the particular issue and theory about its resolution. This process used the Center for Chemical Process Safety's Process Safety Leading and Lagging Metrics (CCPS, 2011), as well as performance measures theorized by the data as inspiration for the proposed measures.

6.4.2. Preliminary Proposed Performance Measures

For each of the theories above, several performance measures were proposed to monitor the safety conditions at a nuclear chemical facilities. The following Tables, 6-1- 6-7 contain the proposed measures for each theory. Table 6-1 presents the proposed performance measures for design and engineering issues.

Table 6-1 | Proposed Performance Measures for Design and Engineering Issues

Memo	Theory	Percentage of Chemical Industry Accident Reports	Associated Codes	Related Preliminary Proposed Performance Measures
EC1- System does not contain design features necessary for safe operation	Ensuring the application of industry standards or best practices in design will improve safety and efficiency of operations at nuclear chemical facilities.	63.4%	Hazard Recognition	-How much time since previous reviews of process or system design -% of processes or systems reviewed in a year
EC4- Materials or equipment design issues	Ensuring the application of industry standards or best practices in material selection and equipment design will improve safety and efficiency of operations at nuclear chemical facilities.	31.7%	Hazard Recognition	-How much time since previous reviews of process or system design -% of processes or systems reviewed in a year
EC9- System not installed according to design or other requirements	Ensuring that the design is followed during the installation of the facility, and checking to ensure it meets specifications will improve safety and efficiency of operations at nuclear chemical facilities.	34.1%	Hazard Recognition, Training	- Percentage of operators and technical staff who are able to identify controls and feel that they understand their operation
EC10- Engineers or professionals participation in design process and knowledge of design standards	Ensuring adequate participation from engineers and design experts in performing design calculations and developing the process design will improve safety and efficiency of operations at nuclear chemical facilities.	34.1%	Hazard Recognition, Training	-Pertinent engineer/technical specialists involved in process reviews or design changes - Percentage of operators and technical staff who are able to identify controls and feel that they understand their operation
SS5- Lack of controls and layers of protection	Ensuring the system has been reviewed for safety and the hazards analysis process has tied safety systems to hazards where necessary will improve safety and efficiency of operation at nuclear chemical facilities.	53.7%	Process Hazard Analysis, Engineering Controls, Maintenance, Mechanical Integrity	-How much time since previous reviews of process or system design -% of processes or systems reviewed in a year - Number of identified hazards and controls reviewed in a given time (relatable to PHA) - Number of corrective

				maintenance requests related to safety systems and controls
SS6- Failure of or lack of alarm system	Ensuring the existence and functionality of alarm systems, including their audibility in all locations of the facility will improve safety and efficiency of operations at nuclear chemical facilities.	31.7%	Process Hazard Analysis, Engineering Controls, Maintenance, Mechanical Integrity	- Amount of time in between inspections or tests of required systems -Planned maintenance that occurs vs. actual maintenance completed -Number of nuisance alarms or false alarms vs. number of valid alarms - Number of corrective maintenance requests related to safety systems and controls
SS9- Failure of or lack of pressure relief devices	Ensuring the proper maintenance and application of pressure relief devices will improve safety and efficiency of operations at nuclear chemical facilities.	34.1%	Process Hazard Analysis, Engineering Controls, Maintenance, Mechanical Integrity	- Amount of time in between inspections or tests of required systems - Planned maintenance that occurs vs. actual maintenance completed -Number of corrective maintenance requests related to safety systems and controls

Table 6-2 presents the proposed performance measures for operating procedures issues.

Table 6-2 | Proposed Performance Measures for Operating Procedures Issues

Memo	**Theory**	**Percentage of Chemical Industry Accident Reports**	**Associated Codes**	**Related Preliminary Proposed Performance Measures**
OP2- Procedure does not contain clear instructions for a part of the process (outdated or incomplete)	Ensuring that procedures are up to date and cover the process step by step will improve safety and efficiency of operations at nuclear chemical facilities.	29.3%	Training, Process Safety Information, and Employee Participation, and Hazards Recognition	-Number of operators or maintenance technicians involved in procedure reviews (as indicated by documentation of the review performed) -% procedures reviewed for content in a year
OP3- Procedure not followed by operators	If operators follow procedures step by step, this action will improve safety and efficiency of operations at nuclear chemical facilities.	34.1%	Training, Process Safety Information, and Employee Participation, and Hazards Recognition	- Number of operators or maintenance technicians involved in procedure reviews (as indicated by documentation of the review performed) - Number of operators or maintenance technicians whose experience is that procedures are current, accurate, and effective (by survey)
OP5- No procedure for abnormal conditions	If procedures are written to anticipate and provide instructions for abnormal operating conditions, it will improve safety and efficiency of operations at nuclear chemical facilities.	34.1%	Training, Process Safety Information, and Employee Participation, and Hazards Recognition	-% procedures reviewed for content in a year
OP6- Procedure does not contain PSI	If operating procedures contain process safety information, it will improve safety and efficiency of operations at nuclear chemical facilities.	29.3%	Training, Process Safety Information, and Employee Participation, and Hazards Recognition	-% procedures reviewed for content in a year

Table 6-3 presents the proposed performance measures for maintenance issues.

Table 6-3 | Proposed Performance Measures for Maintenance Issues

Memo	**Theory**	**Percentage of Chemical Industry Accident Reports**	**Associated Codes**	**Related Preliminary Proposed Performance Measures**
MA3- Maintenance plan is LTA	Adequate maintenance planning will improve safety and efficiency of operations at nuclear chemical facilities.	41.5%	Mechanical Integrity, Engineering Controls	-Number of deferred maintenance requests as a percentage of total maintenance requests - Number of past due maintenance requests as a percentage of total maintenance requests (overdue)
MA4- Performance of maintenance LTA	Ensuring maintenance tasks are carried out as planned will improve safety and efficiency of operations at nuclear chemical facilities.	41.5%	Mechanical Integrity, Engineering Controls	- Percentage of all planned maintenance accomplished in a given time period - Percentage of all safety systems and safety controls planned maintenance accomplished - Percentage of preventive maintenance work that results in corrective maintenance being required -Average amount of time between maintenance requests and completion of maintenance work

Table 6-4 presents the proposed performance measures for mechanical integrity issues.

Table 6-4 | Proposed Performance Measures for Mechanical Integrity Issues

Memo	**Theory**	**Percentage of Chemical Industry Accident Reports**	**Associated Codes**	**Related Preliminary Proposed Performance Measures**
MI5- No MI procedures in place	Ensuring mechanical integrity procedures are in place will improve safety and efficiency of operations at nuclear chemical facilities.	26.9%	Maintenance, Management Oversight, Engineering Controls	- Number of mechanical integrity inspections completed during a time period vs. number of inspections due during that time period
MI6- Equipment repeatedly causes issues	Ensuring the mechanical integrity of all systems will improve safety and efficiency of operations at nuclear chemical facilities.	24.4%	Maintenance, Management Oversight, Engineering Controls	- Amount of time plant is in operation with any safety component in an inoperable or degraded condition (broken down or failed inspection) - Percentage of plant start-ups with no safety problems
MI8- Corrosion or degradation of materials	Ensuring mechanical integrity programs monitor and correct corrosion and degradation problems in a timely manner will improve safety and efficiency of operations at a nuclear chemical facility.	36.6%	Maintenance, Management Oversight, Engineering Controls	- Amount of time plant is in operation with any safety component in an inoperable or degraded condition (broken down or failed inspection) - Percentage of plant start-ups with no safety problems
MI10- Deficiencies corrected in timely manner	Ensuring timely correction of deficiencies will improve safety and efficiency of operations at nuclear chemical facilities.	29.3%	Maintenance, Management Oversight, Engineering Controls	- Amount of time between issuing corrective action and completing the corrective action (deficiencies corrected in a safe and timely manner)

Table 6-5 presents the proposed performance measures for hazards analysis issues.

Table 6-5 | Proposed Performance Measures for Process Hazard Analysis Issues

Memo	**Theory**	**Percentage of Chemical Industry Accident Reports**	**Associated Codes**	**Related Preliminary Proposed Performance Measures**
PHA1- Risks associated with the process not well analyzed by team members	Ensuring that the right subject matter experts are involved in the hazards analysis will improve safety and efficiency of operations at nuclear chemical facilities.	36.6%	Safety systems in Engineering Controls, Training	- Pertinent subject matter experts involved in the DSA development and maintenance (as indicated by document reviews)? - Number of operations and maintenance personnel involved in the DSA development and maintenance (by survey or documented records)?
PHA2- PHA inadequate- i.e. acceptance of lower tier safety controls	Reviewing the hazards analysis to determine if safety controls are appropriately matched to the hazards will improve safety and efficiency of operations at nuclear chemical facilities.	41.5%	Safety systems in Engineering Controls	- Number of USQ process reviews that resulted in formal USQ Determinations (USQDs) - Of those USQDs, were positive USQs actually identified? (Percentage)
PHA4- PHA results not used or updated	Ensuring timely updates to the hazards analysis after changes have been made to the process will improve safety and efficiency of operations at nuclear chemical facilities.	29.3%	Safety systems in Engineering Controls, Training	- Percentage of operators and maintenance techs who have formal training on the DSA?
PHA7- No PHA performed	Ensuring hazards analyses are performed on each process will improve safety and efficiency of operations at nuclear chemical facilities.	46.3%	N/A	(not considered to be an issue in more regulated DOE environment)

Table 6-6 presents the proposed performance measures for incident investigation issues.

Table 6-6 | Proposed Performance Measures for Incident Investigation Issues

Memo	**Theory**	**Percentage of Chemical Industry Accident Reports**	**Associated Codes**	**Related Preliminary Proposed Performance Measures**
II1- Precursor accidents were ignored	Ensuring accident history is studied and occurrences monitored at the facility, including near misses, will improve safety and efficiency of operations at nuclear chemical facilities.	39.0%	Process Hazard Assessment, Process Safety Information, Training	Tracking achieved through ORPS system—no additional performance measure recommended
II2- Lessons learned not applied to new situations in a timely manner, or at all	Ensuring accident history is studied and used to improve existing operations will improve safety and efficiency of operations at nuclear chemical facilities.	31.7%	Process Hazard Assessment, Process Safety Information, Training	- Number of lessons learned developed as a part of review of ORPS reports or other incident reporting - Percentage of operators and maintenance techs who are trained on lessons learned from accidents. (By training records)
II3- No actions taken or tracked based on investigation of previous events	Tracking action items to ensure timely resolution will improve safety and efficiency of operations at nuclear chemical facilities.	24.4%	Process Hazard Assessment, Process Safety Information, Training	- Number of past due safety action items vs. total number of safety action items stemming from previous occurrences

Table 6-7 presents the proposed performance measures for emergency planning and response issues.

Table 6-7 | Proposed Performance Measures for Emergency Planning and Response Issues

Memo	**Theory**	**Percentage of Chemical Industry Accident Reports**	**Associated Codes**	**Related Preliminary Proposed Performance Measures**
EPP1- Lack of emergency plan	Developing and updating a formal emergency plan, as well as ensuring employees are familiar with this plan, will improve safety and efficiency of operations at nuclear chemical facilities.	24.4%	Training, Hazard Recognition	- Amount of time since last update of emergency plan - Number of workers in an operating facility who believe they can confidently execute their responsibilities in an emergency
ERR5- Communication issues with local emergency response	Training and drilling with local emergency responders will improve safety and efficiency of operations at nuclear chemical facilities, particularly in emergency situations.	22.0%	Training, Hazard Recognition	- Number of emergency drills performed in a time period vs. number scheduled (or required) - Number of personnel trained as point person responsible for facility emergency versus the number required? (and/or how many shift managers are trained in this capacity?)
ERR6- Assistance necessary from additional local emergency crews that are untrained	Providing training to local emergency response crews will improve safety and efficiency of operations at nuclear chemical facilities, particularly in emergency situations.	51.2%	Training, Hazard Recognition	- Number of local (county? City?) Emergency Responders trained in facility (e.g. chemical or radiological) hazards and response? -Hours of training available to emergency responders vs. total hours taken
ERR8- Offsite crews injured due to inexperience with hazards or attempting to rescue others without planning	Training offsite crews and communicating with them in advance will improve safety and efficiency of operations at nuclear chemical facilities,	22.0%	Training, Hazard Recognition	-Number of local (county? City?) Emergency Responders trained in facility (e.g. chemical or radiological) hazards and response?

	particularly in emergency situations.			
ERT1- Emergency response crews participate in training with real drills and process information	Providing training to offsite emergency responders on the facility hazards and response protocols will improve safety and efficiency of operations at nuclear chemical facilities.	31.7%	Training, Hazard Recognition	- Number of local (county? City?) Emergency Responders trained in facility (e.g. chemical or radiological) hazards and response? - Hours of training available to emergency responders vs. total hours taken - Number of emergency drills performed in a time period vs. number scheduled (or required)

These proposed performance measures underwent a preliminary review to remove those deemed repetitive or not easily measured at a nuclear chemical facility. This reduction was performed by DOE senior safety and operations subject matter experts who commented on document versions of the performance measures in a guided interview process led by two researchers. The interview process involved a set of questions about areas to be measured, followed by a list of all proposed performance measures listed in the tables above. The senior safety and operations subject matter experts provided feedback on each individual proposed metric and selected a number on a scale for how practical and effective the performance measure would be. The selected numbers for each SME were averaged and the performance measures with a score higher than a 7 (the scale was out of 10) were carried through to the next stage. The interview document is included in Appendix C. The performance measures that were maintained after this process were used during the expert review of the performance measures detailed in Section 6.5.

6.5. Expert Review of Performance Measures

Section 6.5 describes the expert review of the performance measures, both the SME elicitation and the Analytic Hierarchy Process exercise to determine the most practical and effective performance measures for implementation at a nuclear chemical facility.

6.5.1. Introduction

The overall goal of this research was to analyze accidents reports (documentation) from the chemical industry and nuclear chemical facilities (a subset of DOE occurrence reports and NRC abnormal occurrence reports to Congress) for trends to develop a set of predictive or leading safety and performance measures applicable to nuclear chemical facilities. The previous chapters described the data collection and analysis-- analyzing the information presented in the chemical industry accident reports through these varied lenses (i.e., applying the DOE methodology to incidents in the chemical industry, and analyzing the information from DOE occurrence reports). A set of potential safety and performance measures was developed from this process and described previously in Section 6.4. The goal of these integrated safety and performance measures for nuclear chemical operations is to assist in monitoring the safety of facility operations, and thus, help ensure safe and efficient operations at these facilities.

The objective of the subject matter elicitation was the presentation of the derived, proposed performance measures to safety subject matter experts to give them an opportunity to provide factual feedback to further inform the selection of the performance metrics that were most important. These survey responses were also used to refine understanding of proposed performance metrics and add a practical perspective to the qualitative analysis of accident reports. The people surveyed in this research were subject matter experts in the fields of nuclear safety, engineering, nuclear operations and chemical safety. Identified personnel for this study served in positions as DOE safety management professionals, engineers, and operations managers. The methodology for this subject matter expert elicitation was reviewed by the Vanderbilt Internal Review Board (IRB) and received an exemption. The IRB Exemption letter is found in Appendix B.

6.5.2. Methodology

The expert elicitation to improve the proposed performance measures and ensure that they were both practical and effective involved the development and application of a survey tool using analytical hierarchy process (AHP) and an online software program to perform the elicitation. The background and basics of AHP have been described in Chapter 3 of this study. The following sections describe the development and application of the AHP survey and the selection and elicitation of the subject matter experts interviewed in this process.

6.5.2.1. Survey Development and AHP

This application of AHP used the process to rank the overall impact of several categories of performance measures (the objectives), and then under each of those categories, to rank the impact of the proposed performance measures. The subject matter experts were to consider themselves to be the facility manager of a nuclear chemical facility, and rank the objectives and performance measures, as to which would provide them information that would have greater importance to understanding the safe operation of the facility.

The survey administered in the study is an Analytical Hierarchy Process elicitation using the Comparion by Expert Choice software. Participants were guided through the questions. In Comparion, subjects are asked to compare sets of criteria and subcriteria to determine which they considered to be most impactful to safety and efficiency of operations at a nuclear chemical facility. In this study, the criteria are safety management categories and the subcriteria are performance metrics. The structure of the hierarchy used in this analysis is pictured below in Figure 6.2.

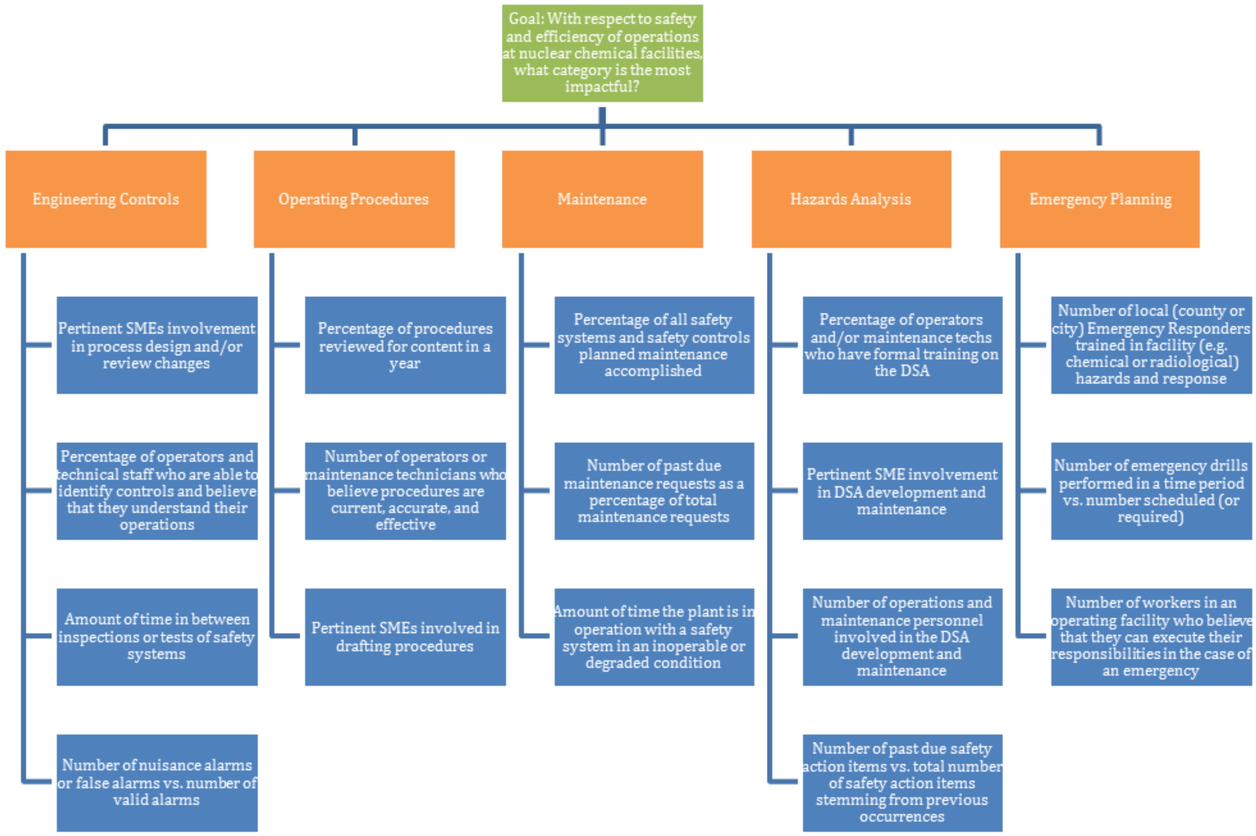


Figure 6.2 | Structure of Analytical Hierarchy Process

The goal of the survey was to analyze, with respect to safety and efficiency of operations at nuclear chemical facilities, what category was the most impactful. Under this goal, there were five categories, composed of those areas from the results of the content analyses determined to be the most impactful to safety and efficiency of operations: engineering controls, operating procedures, maintenance, hazards analysis, and emergency planning. Under each of these objectives, the proposed performance measures were tied to that category.

6.5.2.2. Subject Matter Expert Selection

The subjects that were surveyed in this research were subject matter experts in the fields of nuclear safety, engineering, nuclear operations and chemical safety including DOE safety management professionals, engineers, and operations managers. The participants were identified using a list of subject matter experts familiar with the field and the research objectives (via past interactions). Additional participants were also suggested by the invited subjects. The participation of the DOE subject matter experts included two sites, Hanford and Savannah River. At each facility, a contact was established who was familiar with the research objectives from previous interactions. The contact was selected due to their access to and knowledge of the workforce and ability to suggest knowledgeable subject matter experts to participate. The following list was provided to the two contacts to elicit SMEs for participation:

1. Facility managers
2. Chemical and nuclear safety subject matter experts
3. The managers of the chemical and nuclear safety subject matter experts
4. Experienced facility representatives or their managers
5. Facility system engineers and their managers

The contacts solicited participants from these areas and scheduled them into a multi-day interview visit.

To ensure thoughtful and honest responses to the survey questions, the participants were interviewed one at a time in a private setting, and guaranteed anonymity. No personal data related to the subject was maintained as a part of the survey process. The survey response data was not tied to the individual in any written or electronic documentation. Some data was monitored about the participant including the following metrics:

1. DOE/Contractor
2. Safety SME/Operations
3. Manager/Employee
4. Site or HQ

This information was used for trending purposes only.

A set of criteria paragraphs summarizing the results described in Chapters 4 and 5 of this study was provided to the SMEs in advance of the survey to provide context and background information for the elicitation and responses. The SMEs were also provided the opportunity to discontinue participation in the study at any time, and provided verbal consent to participate, witnessed by two researchers present at the elicitation. The criteria paragraphs are included below in 6.5.2.b.1

6.5.2.b.1 Criteria Paragraphs

Criteria Paragraphs for SME elicitation

Design and Engineering Controls

Design and Engineering Controls is an OSHA Process Safety Management derived category that includes issues with process design and engineering as well as safety systems design and engineering. There are several requirements for design and engineering, including that the DOE contractor: document that equipment complies with recognized and generally accepted good engineering practices and determine and document that the equipment is designed, maintained, inspected, tested, and operating in a safe manner. For safety systems, the DOE contractor should ensure that there are engineering and administrative controls applicable to the hazards and their interrelationships such as appropriate application of detection methodologies to provide early

warning of releases. A major program within the DOE that addresses this area is the Cognizant System Engineer program, which assigns engineers who are responsible for maintaining overall cognizance of assigned systems, providing systems engineering support for operations and maintenance, and technical support of line management safety responsibilities for ensuring continued system operational readiness. System design documents and supporting documents must be identified and kept current using formal change control and work control processes. DOE-STD-3024-2011, Content of System Design Descriptions, describes an acceptable methodology to achieve this function. DOE O 420.1C also establishes requirements for the design and construction of safety-SSCs, both safety-class and safety-significant, by identifying an applicable set of industry codes and standards, as well as Department of Energy (DOE) design criteria, standards and directives.
This research has illustrated that design and engineering issues that result in accidents tend to be related to: (1) a lack of design features or safety controls, (2) a lack of adequate participation from engineers and design experts in performing design calculations and developing the process design, and (3) failure of safety systems such as pressure relief devices or alarm systems and (4) underdesign of safety systems, i.e. insufficient layers of protection.

Operating Procedures

Operating Procedures is an OSHA Process Safety Management (PSM) based category. To be consistent with PSM for operating procedures, a DOE contractor should develop and implement written operating procedures that provide clear instructions for safely conducting activities involved in each covered process, that incorporates necessary process safety information and must address at least the following elements: steps for each operating phase, operating limits, safety and health considerations, and safety systems and their functions. Further, operating procedures must be readily available, reviewed as often as necessary to ensure accuracy, but no less than once per year, and safe work practices for control of hazards during operations must be established. DOE Order 422.1, Conduct of Operations, and DOE-STD-1029-92, Writer's Guide for Technical Procedures, provide the Departments expectations regarding operating procedures and their implementation and involve similar considerations. DOE STD-1029-92 requires that a DOE contractor must establish and implement operations practices for developing and maintaining accurate, understandable written technical procedures that ensure safe and effective facility and equipment operation, addressing the following elements: expectations for the use of procedures to perform operations; a process for procedure development; procedure content, including consistent format and use of terms (e.g. prerequisites, warnings, cautions, notes, hold points, etc.), detail sufficient for accomplishing the operation, technically accurate procedures capable of performance as written, and procedure conformance with the facility design and manufacturer documentation; a process for procedure changes (pen and ink or page changes) and revisions (complete reissues); a process for training personnel on new, revised, or changed procedures; a process for approval of new, revised, or changed procedures; initial-issue and periodic review and testing of procedures; availability and use of the latest revisions of procedures; and specified and defined procedure use requirements, i.e., reader-worker method, reference use only, use-each-time, and emergency response.

In these reports, issues with operating procedure tend to be related to: (1) operators failing to follow procedures, (2) outdated or ineffective procedures, (3) a lack of safety information in the procedure, and (4) a lack of procedural information for abnormal circumstances (such as a higher than anticipated temperature or pressure reading).

Maintenance

Maintenance is not an OSHA PSM category, although the related subject mechanical integrity is identified and has several requirements for compliance. Requirements related to maintenance include: that the DOE contractor will establish and implement written procedures to maintain the on-going operability of process and safety equipment and that the DOE contractor will train each employee involved in maintaining the on-going operability of process and safety equipment by providing an overview of the process and its hazards, and the applicable procedures to assure that the employee can perform the job tasks in a safe manner. DOE Order 433.1B describes the maintenance management program required for maintenance and the reliable performance of structures, systems and components that are part of the safety basis required by at hazard category 1, 2 and 3 Department of Energy (DOE) nuclear facilities. DOE G 433.1-1A, Nuclear Facility Maintenance Management Program Guide for Use with DOE O 433.1, provides acceptable approaches for meeting the requirements of the order using 17 elements, the most relevant to this work include: Planning, Scheduling, and Coordination of Maintenance; Types of Maintenance; Maintenance Procedures; Aging Degradation and Technical Obsolescence; and Performance Measures.
Observed maintenance issues tend to be related to (1) a lack of maintenance planning, or (2) less than adequate performance of maintenance jobs.

Hazards Analysis

The category of hazards analysis is consistent with the OSHA PSM standard for Process Hazard Analysis (PHA). To be in compliance with PSM, OSHA requires an initial process hazard analysis (hazard evaluation) on processes covered by the standard and that the process hazard analysis be appropriate to the complexity of the process and identify, evaluate, and control the hazards involved in the process. It further requires operators to determine and document the priority order for conducting process hazard analyses based on a rationale which includes such considerations as the extent of the process hazards, number of potentially affected employees, age of the process, and operating history of the process. The DOE requirements for Hazard Analysis reside in DOE-STD-3009, Section 3.1. DOE-HDBK-1100-2004 describes how various DOE programs combine to meet the intent of PSM. The Hazard Analysis is the initial analytical effort for all facilities that systematically identifies and evaluates facility hazards, potential accidents, and controls. The hazard evaluation focuses on evaluating the complete spectrum of hazards and accidents. The guidance in DOE-HDBK-1100-2004 uses the OSHA PSM Rule, discussed above, as a guide for developing DOE Chemical Hazards Analysis.
The most common issue that we observed in the area of hazards analysis (HA) is that no hazards analysis was performed. While this may be less of an issue in the DOE environment; for example, due to the implementation of Integrated Safety Management (ISM), other observations included: (1) inadequacies in the HA, such as the acceptance of lower tier safety controls for certain scenarios and a (2) lack of necessary expertise in the team performing the assessment. We also observed that many facilities involved in accidents did not have a system in place to update these assessments and track the implementation of findings from them.

Emergency Planning

Emergency Planning is an OSHA PSM based category that includes both planning and response for emergency situations. To be in compliance with OSHA PSM, an operator should establish and implement an emergency action plan for the entire plant and include procedures for handling small releases. DOE Guide 151.1-1A, The DOE Emergency Management Program Guide, offers guidance for Emergency Planning at DOE facilities. The major relevant components of the DOE Emergency Management Program are: Planning- determining, in advance, what will be done in response to specific emergencies; Preparedness- putting in place procedures, equipment, and personnel capabilities that will be needed to respond; and Readiness Assurance- the ongoing process of verifying and demonstrating readiness to respond.
This research indicated that emergency planning and response issues in the chemical industry tend to be centered around: (1) a lack of emergency planning, (2) employees who are unsure of what to do or who to contact, and (3) communication issues and confusion among emergency responders; these are coupled with the emergency response issues concerning (4) a lack of training and lack of resources for emergency responders, leaving them unsure of the hazards and not able to provide the most efficient assistance to the facility.

6.5.2.3. The Elicitation

The elicitation involved the participation of two researchers in a private one on one setting with the SME. To perform the interviews, the two researchers traveled to the work site of the SMEs. During the elicitation, one researcher read from a script for consistency of delivery from subject to subject. This researcher also entered the data into the web based survey tool. The second researcher participated by responding to questions or comments throughout the process and notated verbal comments and suggestions. A copy of the survey tool is included at the end of this study in Appendix D.

The survey tool asked three types of questions:

The first set included comparative questions regarding focus areas: for example, "In regards to safety and efficiency of operations at a nuclear chemical facility, which of the following types of performance measures would have a greater impact: (1) Mechanical integrity of safety systems or (2) Process Safety Information Availability?" The computer screen showed these two choices on either end of a sliding scale, and the SME would make a selection from the scale to fit their thoughts.

In the second section, the focus area was replaced with the proposed performance metrics developed, and use the same sliding scale. For example, "In regards to safety and efficiency of operations at a nuclear chemical facility, which of the following performance metrics would have a greater impact: (1) Number of occurrences reported in the last calendar year or (2) Percentage of occurrences involving worker injuries in a calendar year?" The response was entered the same as before, on the computer using the sliding scale.

The third section was an open ended question to gather feedback about the tool and any comments about performance measures that may be important to the SME but were not covered in the other areas. Also, throughout the elicitation, there was time provided for feedback and comments about the proposed metrics or the process.

A screen shot of what the interviewee saw on the computer screen is included in Figure 6.3 below. Adjustments to the scale were made toward the preferred performance metric.

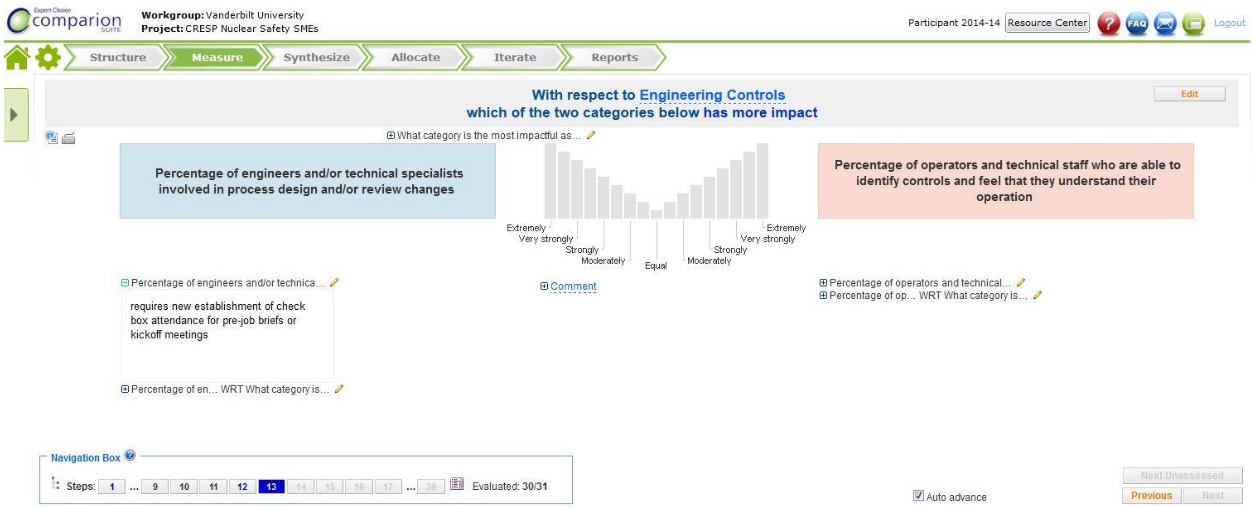


Figure 6.3 | Screenshot of Comparion by Expert Choice Interview

Upon completion of the survey, the participants were again invited to offer comments about the proposed performance metrics or the process, and offer feedback about additional or alternative performance measures currently employed at their facility.

6.5.3. Results

The results from the SME elicitation using an AHP architecture were collected during site visits to the locations and are presented below. The first results presented are the rankings of the categories of the performance measures. These are followed by the individual performance measures under each category. The final results of this SME elicitation include the shortened list of performance measures deemed practical and effective by the SMEs. Figure 6.4 illustrates the overall ranking of the categories for potential performance measures.

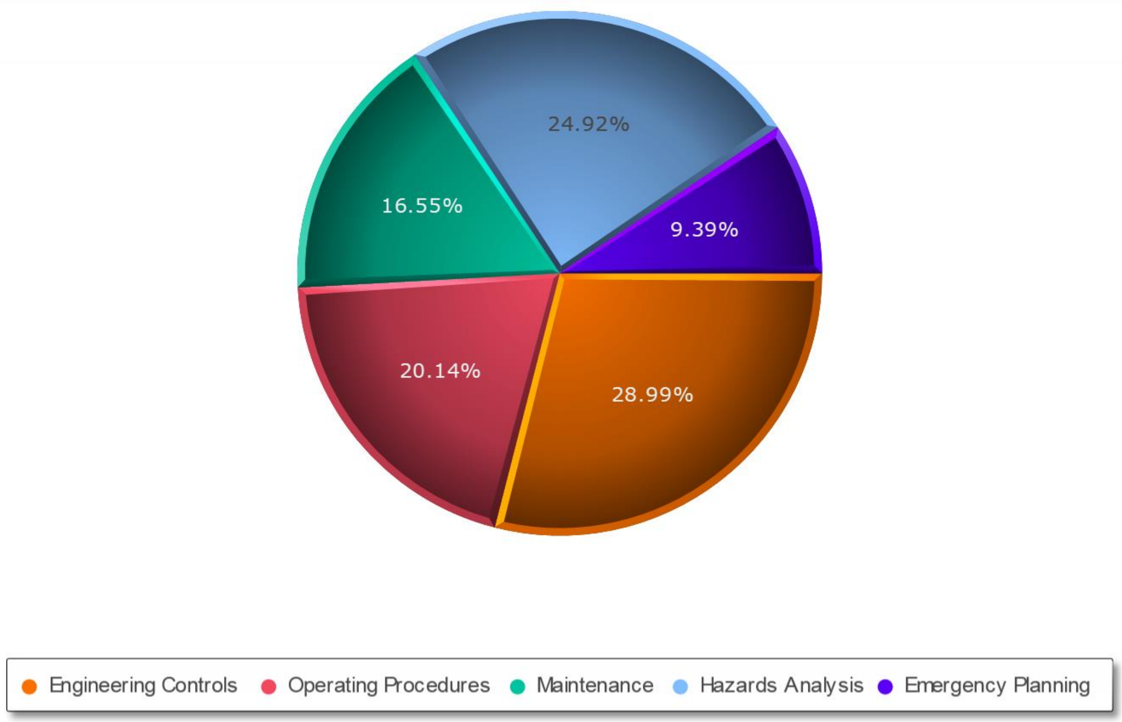


Figure 6.4 | Overall Ranking of the Potential Performance Measure Areas

6.5.3.1. Performance Measure Preferences

The SMEs interviewed Prioritized Engineering Controls Performance Measures above other categories of performance measures. They ascribed equal priority to Operating Procedures, Maintenance, and Hazards Analysis Performance Measures. The Emergency Planning Performance Measures were given lowest overall priority. In each of these areas, we will highlight those performance measures which were above the median value for the analysis. The Engineering Controls performance measures preferences are illustrated in Figure 6.5.

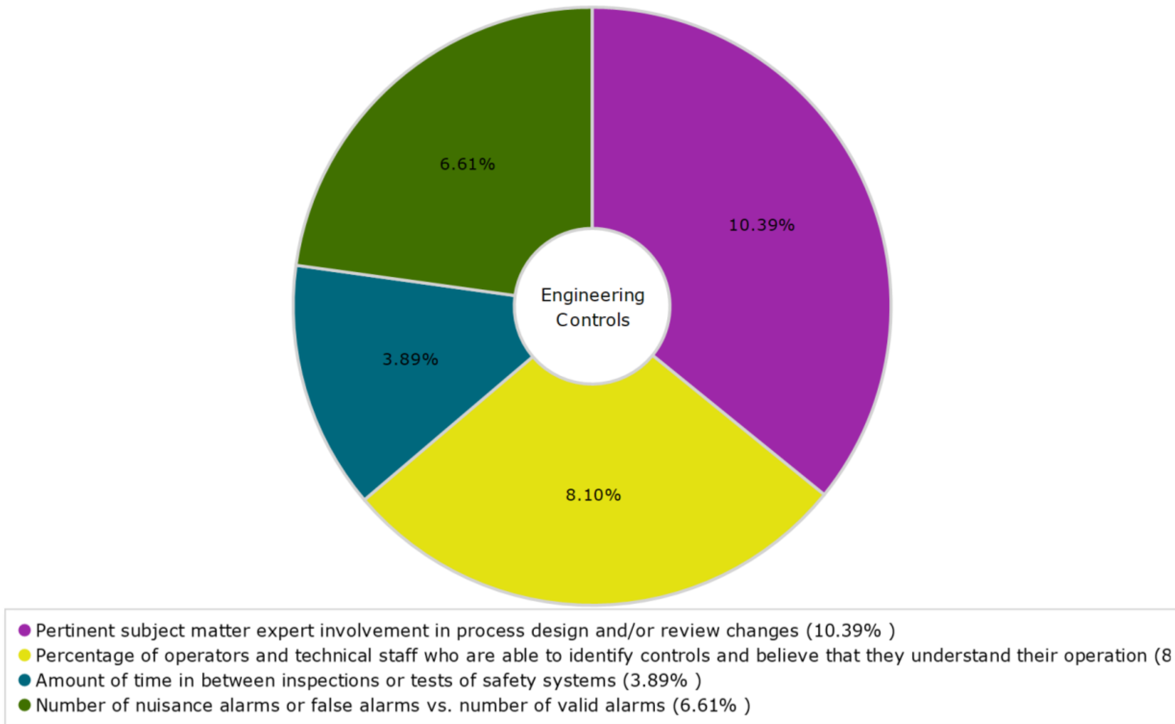


Figure 6.5 | Ranking of Engineering Controls Proposed Performance Measures

Three performance measures in Engineering Controls were above the median value:

- Pertinent SMEs involvement in process design and/or review changes
- Percentage of operators and technical staff who are able to identify controls and believe that they understand their operations
- Number of nuisance alarms or false alarms.

These performance measures represented the most preferred engineering controls performance measures by the SMEs. They became the recommended engineering controls performance measures for nuclear chemical facilities, listed again in Section 6.6. Recommendations for measuring and tracking these performance measures at a nuclear chemical facility are discussed in Chapter 8.

The Operating procedures performance measure preferences are illustrated in Figure 6.6.

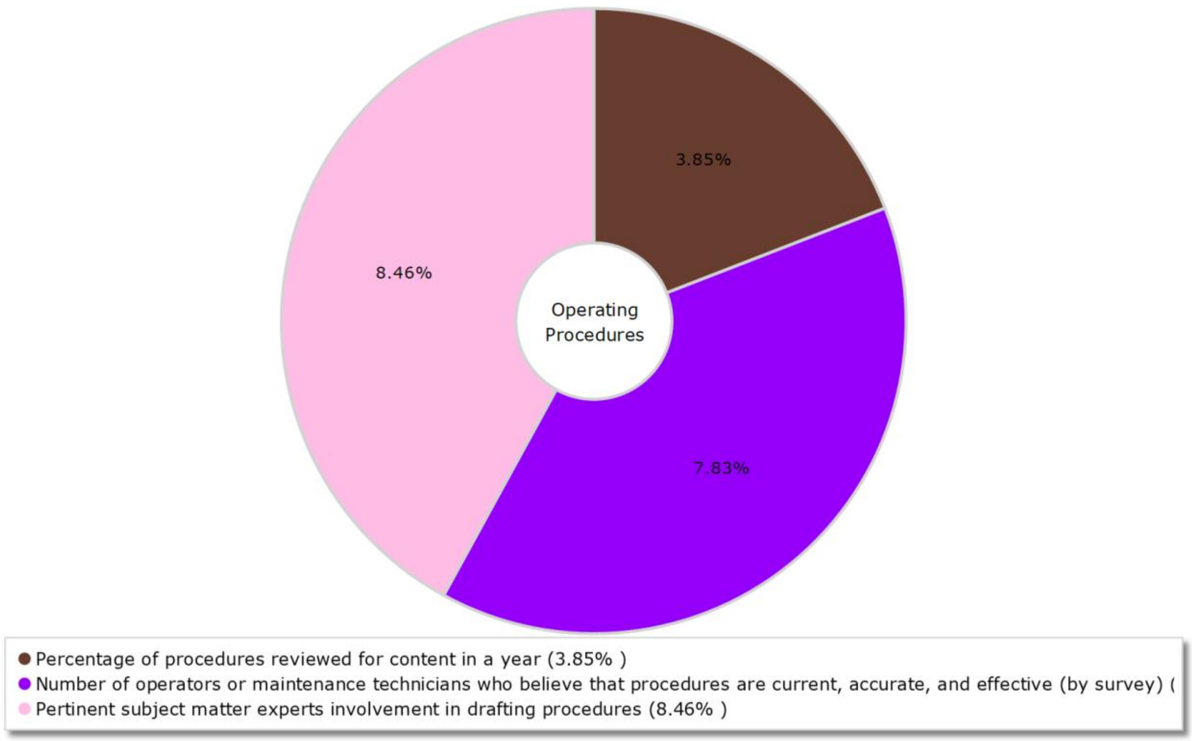


Figure 6.6 | Ranking of Operating Procedures Proposed Performance Measures

Two performance measures were above the median value:

- Number of operators or maintenance technicians who believe procedures are current, accurate, and effective
- Pertinent SMEs involved in drafting procedures.

These performance measures represented the most preferred operating procedures performance measures by the SMEs. They became the recommended operating procedures performance measures for nuclear chemical facilities, listed again in Section 6.6. Recommendations for measuring and tracking these performance measures at a nuclear chemical facility are discussed in Chapter 8.

The Maintenance performance measure preferences are illustrated in Figure 6.7.

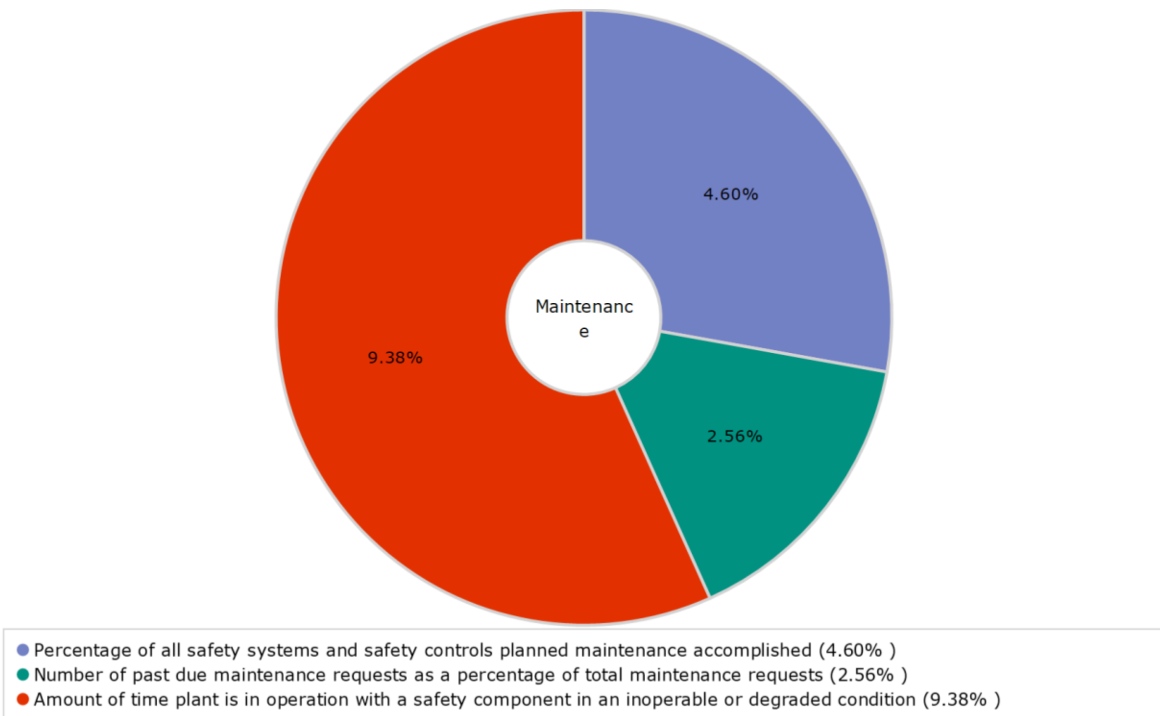


Figure 6.7 | Ranking of Maintenance Proposed Performance Measures

One performance measure was above the median value:

- Amount of time the plant is in operation with any safety system in an inoperable or degraded condition.

This performance measure represented the most preferred maintenance performance measures by the SMEs. It became the recommended maintenance performance measure for nuclear chemical facilities, listed again in Section 6.6. Recommendations for measuring and tracking this performance measures at a nuclear chemical facility are discussed in Chapter 8.

The Hazards Analysis performance measure preferences are illustrated in Figure 6.8.

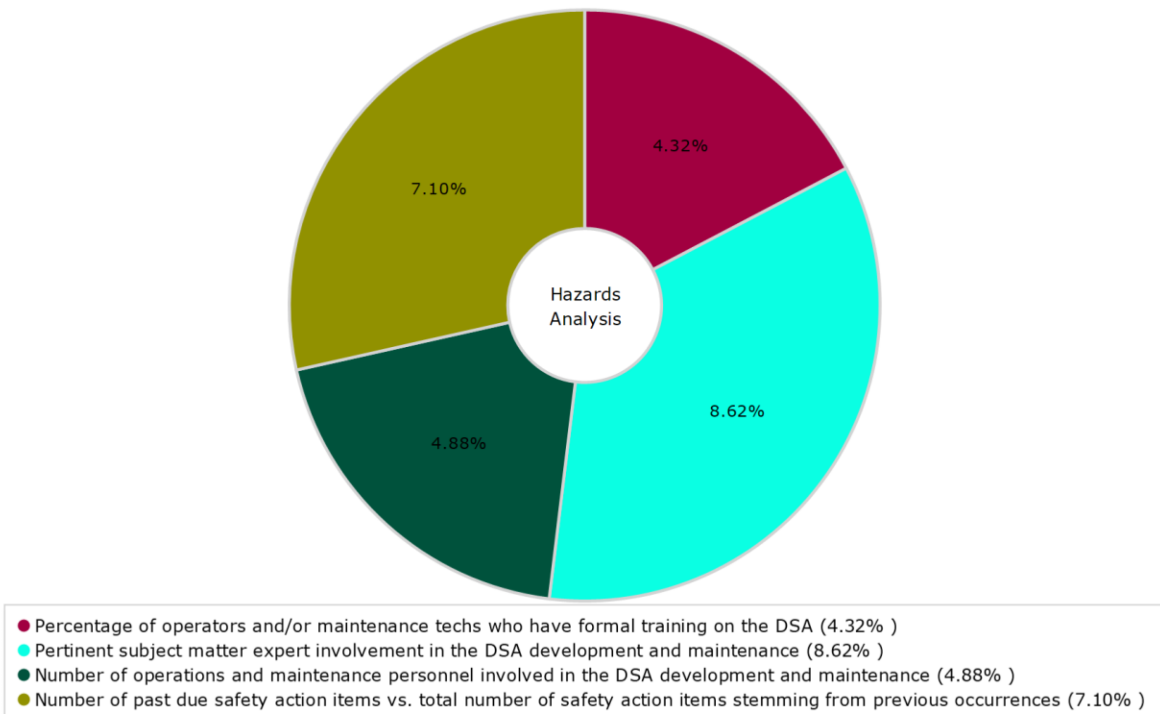


Figure 6.8 | Ranking of Hazards Analysis Proposed Performance Measures

Two performance measures were above the median value:

- Pertinent SME involvement in DSA development and maintenance.

- Number of past due safety action items vs. total number of safety action items stemming from pervious occurrences

These performance measures represented the most preferred hazards analysis performance measures by the SMEs. They became the recommended hazards analysis performance measures for nuclear chemical facilities, listed again in Section 6.6. Recommendations for measuring and tracking these performance measures at a nuclear chemical facility are discussed in Chapter 8.

The Emergency Planning and Response performance measure preferences are illustrated in Figure 6.9.

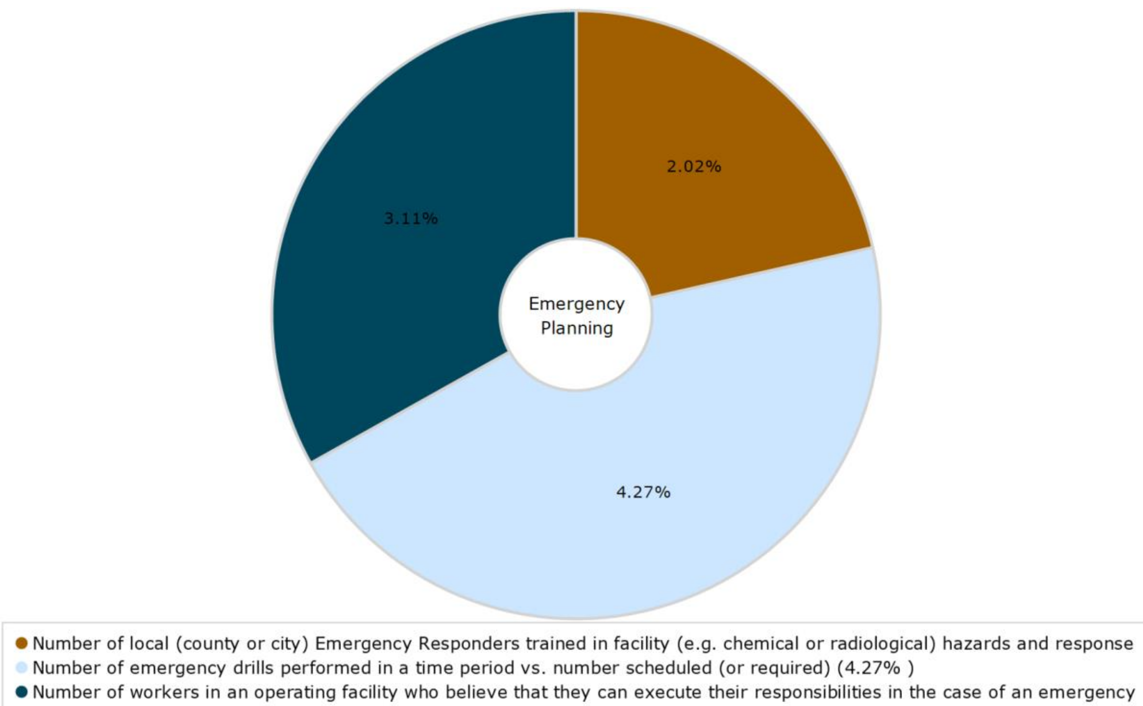


Figure 6.9 | Ranking of Emergency Planning and Response Proposed Performance Measures

There were no emergency planning performance measures above the median.

Thus, no emergency planning performance measures were recommended in the final list in Section 6.6. However, the fatalities of emergency responders in the studied chemical industry accident inspired a series of recommendations for emergency response and planning at nuclear chemical facilities. These recommendations are detailed in Chapter 7.

6.5.3.2. Notes of Interest

There was a slight difference in response depending on the background and experience of the SME. For example, Table 6-8 illustrates the difference in priorities from safety and operations SMEs.

Table 6-8 | Operational Perspective vs. Safety Perspective Rankings of Top Level Criteria

Top Level Criteria	**Operational Perspective Priorities**	**Safety Perspective Priorities**
Engineering Controls	28.11%	29.37%
Operating Procedures	*24.06%*	*18.50%*
Maintenance	18.17%	15.35%
Hazards Analysis	*19.91%*	*27.46%*
Emergency Planning	9.75%	9.33%

Table 6-8 illustrates that the Operational perspective SMEs ranked operating procedures over hazards analysis by about 6%. The Safety perspective SMEs ranked hazards analysis over operating procedures by about 9%. Despite this difference, the other 3 areas were fairly consistently ranked, varying only 2-3%.

Another comparison that yielded interesting results was the federal employee vs. the contractor priorities. These are displayed in Table 6-9 below.

Table 6-9 | Federal Employee vs. Contractor Rankings of Top Level Criteria

Top Level Criteria	**Federal Employee Priorities**	**Contractor Priorities**
Engineering Controls	28.52%	28.87%
Operating Procedures	*21.43%*	*18.63%*
Maintenance	15.60%	16.59%
Hazards Analysis	*22.79%*	*27.88%*
Emergency Planning	*11.67%*	*8.03%*

The contractors tended to place more emphasis on the hazards analysis performance measures than the federal employees and less on emergency planning and operating procedures. The two groups were in agreement over the relative importance of maintenance and engineering controls, as well as the overall ranking of the areas.

Another interesting result of the analysis was the preference of the SMEs for performance measures related to ensuring that the right people were involved in these areas. Of the 8 preferred performance measures, 3 related to SME participation and involvement in these areas and 2 related to ensuring operators and maintenance technicians had an understanding and method to provide feedback. In other words, 5 of the 7 preferred performance measures were related to the people involved the in the processes, rather than the equipment or safety management systems in place.

There were several potential biases involved in the survey results:

1. Background Bias- Participants were asked to put themselves in the shoes of a facility manager to help them overcome the focus of their background
2. Sequence Bias- Some participants compared the issues in the sequence in which they would approach them at the facility– Hazards Analysis→ Engineering Controls → Operating Procedures → Maintenance → Emergency Planning. These SMEs tended to put more emphasis on the early sequence performance measures.
3. Static vs. Dynamic Systems Bias- Some participants viewed some issues as static (Engineering Controls, Hazards Analysis) and others as dynamic (Maintenance, Operating Procedures, Emergency Planning). These SMEs tended to put more emphasis on dynamic areas that they felt required more focus from performance measures because they could change.

6.6. Most Impactful Performance Measures

After collecting SME input and calculating the results, 8 proposed performance measures were carried through as being both practical and effective means of determining the status of safety at nuclear chemical facilities. These performance measures are listed below.

- Engineering Controls
    - Pertinent SMEs involvement in process design and/or review changes
    - Percentage of operators and technical staff who are able to identify controls and believe that they understand their operations
    - Number of nuisance alarms or false alarms
- Operating Procedures
    - Number of operators or maintenance technicians who believe procedures are current, accurate, and effective
    - Pertinent SMEs involved in drafting procedures
- Maintenance
    - Amount of time the plant is in operation with any safety system in an inoperable or degraded condition
- Hazards Analysis
    - Pertinent SME involvement in DSA development and maintenance

- Number of past due safety action items vs. total number of safety action items stemming from pervious occurrences

The performance measures listed were further vetted using a quantitative application of probabilistic risk assessment. This process is described in Chapter 7 of this study. Chapter 7 also contains recommendations for applying these performance measures to a nuclear chemical facility.

CHAPTER 7

ASSESSMENT AND IMPLEMENTATION OF PERFORMANCE MEASURES

7.1. Introduction

Chapters 4-6 laid the foundation and proceeded through the development of performance measures to improve safety and efficiency of operations at nuclear chemical facilities. The process of collecting feedback and input from subject matter experts at nuclear chemical facilities served as a quality check, to ensure that the performance measures proposed were practical and effective measures to monitor. However, the analysis to this point did not provide any information about quantifying the reduction in risk that could be achieved from these performance measures. Further, no information has been provided about applying these performance measures at a facility, for example, the collection of data and the formation of baselines that would be used to determine if safety conditions are degraded.

The objectives of Chapter 7 are to answer two questions: (1) can we demonstrate that these performance measures could provide a measurable reduction in the risks associated with operating these facilities to illustrate their efficacy? and (2) what steps would we take, and what changes would we make to use these performance measures at a nuclear chemical facility? This chapter covers the efficacy of performance measures in reducing risk and improving safety at nuclear chemical facilities, as well as the practicality of measuring and monitoring the proposed quantities to make judgments on the safety status of the operating facility.

The outline of Chapter 7 is as follows:

7.2 Quantitative Risk Assessment of Performance Measures

7.3 Application of Performance Measures at DOE nuclear chemical facilities

7.4 Additional considerations to improve safety and efficiency of operations at nuclear chemical facilities

7.2. Quantitative Risk Assessment of Performance Measures

Section 7.2 describes the quantitative assessment of the impact of the performance measures through their application to a probabilistic risk assessment.

7.2.1. Introduction

One method to determine the quantitative risk associated with an operating facility is to use Probabilistic Risk Assessment (PRA), a process described in Chapter 3 of this study. In order to determine the quantitative effect of the proposed performance measures on risk at a nuclear chemical facility, one such PRA was used. The PRA for the Defense Waste Processing Facility (DWPF) at the DOE Savannah River was completed in 1995 by a team of government and contractor experts to provide a quantitative measure of the risk associated with DWPF operations (Sarrack, 1995).

DWPF is an operational facility at the Savannah River Site, and meets the definition in the context of this study as a nuclear chemical facility, meaning its process intertwines complex chemical operations with radiological materials and associated hazards. The purpose of DWPF is to convert liquid high level nuclear waste, stored at the tank farms at the Savannah River Site, into a solid glass form that is stable for long term storage or disposal. DWPF has been operational since 1996, and some of the nuclear chemical occurrences studied in Chapter 5 occurred at DWPF.

Safety of operations is and was a predominant concern for the DOE. As a part of the safety analysis process for DWPF, several hazards analyses were conducted to determine hazards to human health or the environment. These fed into the safety analysis report, which identifies and quantifies the consequences and frequency of studied accident sequences and ensures adequate controls are available, active and passive, engineered and administrative, to reduce the likelihood and consequences of these events. As a part of this safety assurance process, a PRA was completed for DWPF, providing a probabilistic representation of the accident sequences that may be involved in one of these events. The PRA cites the three barriers to the release of fission products to the environment at DWPF, to include: the process vessels and piping [the primary barrier], the DWPF buildings, and the ventilation/filter system. The main accidents of concern are energetic events from the deflagration or detonation of hydrogen or benzene vapors produced in the process vessels Taylor and Massey, 1996, Page 1).

The PRA contains several accident progression event trees (APET) that illustrate possible progression of the events. In the development of an APET, a series of events [questions] was postulated that could occur during progression of the accident. These events pertain to (Taylor and Massey, 1996, Page 2):

1. the cause of the accident [i.e., initiating event],
2. the status of the plant at the time of the accident,
3. the energetics of the accident,
4. the impact of the accident on adjacent equipment/processes, and
5. the response of the Confinement System to the challenge posed by the energetics accompanying the accident and/or the radionuclides that breach the primary barrier.

In the APET, a probability of occurrence was assigned to each of the events above based on: known information related to the condition of the facility or the accident under consideration, fault tree analysis of active systems within the facility, the answers to previous questions [i.e., accident progression is sequence dependent], and/or mechanistic analysis of accident phenomena and confinement response (Taylor and Massey, 1996, Page 2). Several APETs from this PRA formed the basis for the quantitative demonstration of risk reduction from the proposed performance measures that follows. The APETs were analyzed to determine if the addition of the performance measures affected the quantitative probability of the accident. Modeling of the APETs with revised nodes reflected in the error probabilities was performed to illustrate that the performance measures could have an impact on the quantitative risk at a nuclear chemical facility. The analysis described hereafter is for illustrative, and not regulatory purposes. The quantitative changes were not designed to have an effect on the operational safety basis of the facility, rather to further inform performance measure development and implementation.

7.2.2. Quantitative Assessment

The PRA for the DWPF at the Savannah River Site was used in this analysis to determine whether the proposed performance measures resulted in quantitative risk reductions. From this PRA, three APETs were chosen representing three separate event scenarios at DWPF: these included a steam explosion in the melter (Sarrack et al, 1995, Page 364), an explosion in the low point pump pit in the precipitate pump tank (Sarrack et al, 1995, Page 414), and a benzene explosion in the salt processing cell (Sarrack et al, 1995, Page 446). Each of these events are described in more detail below. The full APETs for these three events are included in Appendix D of this study.

For each APET, the first process was to take one performance measure and select nodes that could potentially be impacted by monitoring the data recommended for that measure. Once the nodes were identified, each node was traced back to the source of the data for the quantitative frequency. This frequency was then evaluated to determine whether it could be adjusted based on improvements in operations/safety produced by implementing the performance measure.

7.2.2.1. Steam Explosion in the Melter

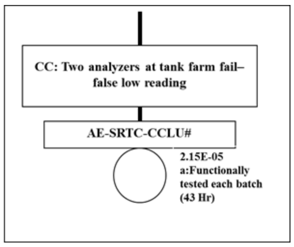
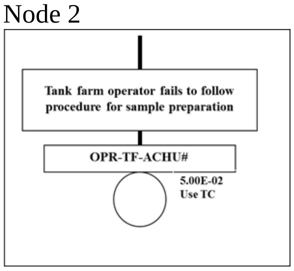
The following discussion of the steam explosion in the melter is described in the DWPF Event Tree Report (Sarrack et al, 1995, Page 12):

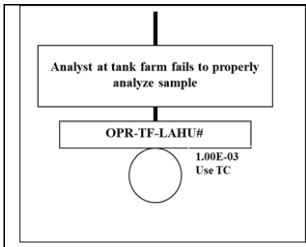
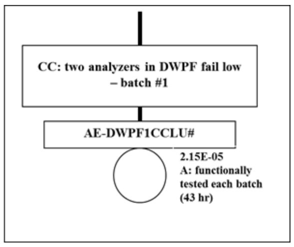
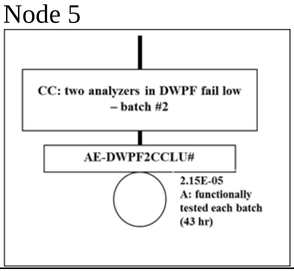
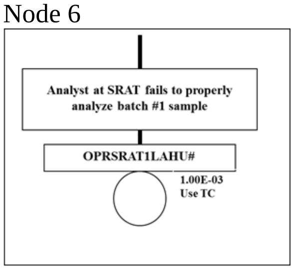
> "Conditions that could lead to a steam explosion in the melter require the presence of both water and partially melted excess salt. Water is a normal constituent of the-process. Melter feed is a slurry which is approximately 50% water. Also procedures require

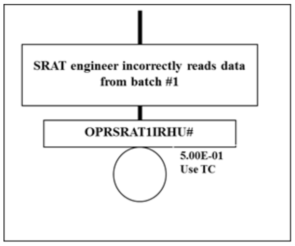
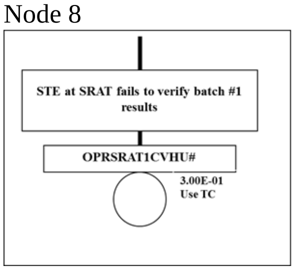
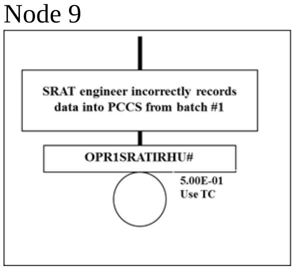
flushing of the feed tube with water before and tier each feed operation. Salt content is monitored by sampling and controlled by procedures in both the Liquid Radioactive Waste Handling Facilities (LRWHF) and DWPF."

The APET for the steam explosion in the melter contains both human errors and sampling equipment errors. There are several nodes which could be impacted by the proposed performance measures. Table 7-1 lists the nodes and proposed changes to the probabilities associated with them and can be used to estimate how a nuclear chemical facility functioning with the recommended performance measures might have a reduced probability of the event. Table 7-1 also shows the sensitivity of this overall probability change for each potentially affected node. In total, this APET had 18 input nodes. Of these 18, 9 were modeled improved by the performance measures.

Table 7-1| Steam Explosion in the Melter Affected Nodes and Probability Changes

Node	**Source of data for probability and assumptions**	**Impact of performance measure on assumptions**	**Rationale**	**Revised probability estimate** **Percent Change of Overall Event Probability for node (%)**
Node 1 	The source of the current error probability is the Sensor Level Failure LST-FA-1 in the Savannah River Site Generic Database Development from 1993 (Blanton and Eide, 1993). The current value (as shown above) is 2.15E-5, which assumes a 5.0E-7H failure rate where H is 86 hours for the analyzer (43 hours for both).	With the addition of Engineering Controls performance measures to ensure controls are designed by the right subject matter experts, and maintenance controls to ensure the analyzers are maintained, the analyzer could be assumed to be more reliable.	According to the 1996 version of the Savannah River Site Generic Database Development document, a 50% to 75% reduction in component failure rates has been observed in system/facilities with successful predictive and/or precision maintenance program (Blanchard, 1996, Page 11). Thus, with the increased engineering design protocol and addition of maintenance performance measures, we will model a reduction of 50% of the current failure rate.	1.1E-5 2.16
Node 2 	The source for the current error probability is the Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities from 1994, listed in Table 4 of that report (Benhardt et al, 1994). The current value is the high probability estimate for Failure of an Administrative Control.	With the addition of the two operating procedures performance metrics, the sample preparation procedure should be current, accurate and effective and revised or developed using the right subject matter experts. With these additional controls in mind, a reduction in probability for this node may be warranted.	Benhardt recommends the use of the high value for unusual circumstances. The use of the nominal value, rather than the high value is modeled, as recommended in Benhardt for typical circumstances.	5.0E-03 4.30
Node 3	The source for the current error	With the addition of the two operating	With these additional controls in mind, a	3.0E-04

	probability is the Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities from 1994, listed in Table 4 of that report (Benhardt et al., 1994). The current value is the high probability estimate for Laboratory Analysis Error.	procedures performance metrics, the sample analysis procedures should be current, accurate and effective and revised or developed using the right subject matter experts.	reduction in probability for this node may be warranted. For the high estimate, the error of omission or commission was used directly, which implies no check of the analysis (Benhardt, 1994). The use of the nominal value, rather than the high value is modeled.	0.27
Node 4 	The source of the current error probability is the Sensor Level Failure LST-FA-1 in the Savannah River Site Generic Database Development from 1993 (Blanton and Eide, 1993). The current value is 2.15E-5, which assumes a 5.0E-7H failure rate where H is 86 hours for the analyzer (43 hours for both).	With the addition of Engineering Controls performance measures to ensure controls are designed by the right subject matter experts, and maintenance controls to ensure the analyzers are maintained, the analyzer could be considered to be more reliable.	This would be similar in improvement to Node 1.	1.1E-5 1.62
Node 5 	Node 5 is functionally the same as Node 4. See above.	Node 5 is functionally the same as Node 4. See above.	Node 5 is functionally the same as Node 4. See above.	1.1E-5 1.62
Node 6 	The source for the current error probability is the Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities from 1994, listed in Table 4 of that report (Benhardt et al., 1994). The current value is the high probability estimate for Laboratory Analysis Error.	With the addition of the two operating procedures performance metrics, the sample analysis procedures should be current, accurate and effective and revised or developed using the right subject matter experts.	With these additional controls in mind, a reduction in probability for this node may be warranted. For the high estimate, the error of omission or commission was used directly, which implies no check of the analysis (Benhardt, 1994). The use of the nominal value, rather than the high value is modeled.	3.0E-04 0.98

Node 7  	The source for the current error probability is the Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities from 1994, listed in Table 3 of that report (Benhardt et al., 1994). The current value is the high probability estimate for Incorrect Reading or Recording of Data.	With the addition of the two operating procedures performance metrics, and the engineering controls metrics, the analyst will find analysis procedures that are effective and be familiar with these, and will also be familiar with the controls on the system and understand the important of checking and double checking this measurement.	With these additional controls in mind, a reduction in probability for this node may be warranted. The high value is recommended for a poorly designed display, under very high stress conditions inside a control room, or for a poorly designed display, under nominal conditions outside the control room (Benhardt, 1994). The use of the nominal value (a good display), rather than the high value is modeled.	1.0E-02 ——— 88.1
Node 8  	The source for the current error probability is the Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities from 1994, listed in Table 4 of that report (Benhardt et al., 1994). The current value is the high probability estimate for Checker Verification Error.	With the addition of the two operating procedures performance metrics, the sample analysis procedures should be current, accurate and effective and revised or developed using the right subject matter experts.	With these additional controls in mind, a reduction in probability for this node may be warranted. The high value includes as assumption that written materials are not used (Benhardt, 1994). The use of the nominal value (alerted, but not active participant), rather than the high value is modeled.	1.0E-01 ——— 60.0
Node 9  	The source for the current reading is the Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities from 1994, listed in Table 3 of that report (Benhardt et al., 1994). The current value is the high probability estimate for Incorrect Reading or Recording of Data.	With the engineering controls metrics, the engineer will be familiar with the controls on the system and understand the importance of checking and double checking this measurement.	With these additional controls in mind, a reduction in probability for this node may be warranted. The use of the nominal value (good display), rather than the high value (poor display) is modeled.	1.0E-02 ——— 88.1

With all potentially affected nodes included in the analysis, the new probability of the steam explosion in the melter may be as low as 1.22 E-6 per year. This compares to the previous probability of 1.82E-5 per year without the changes implemented due to the performance measures.

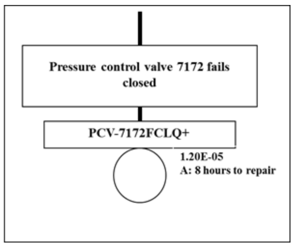
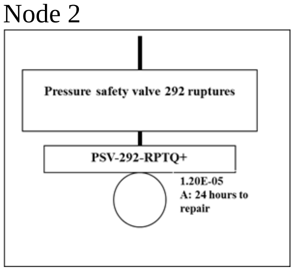
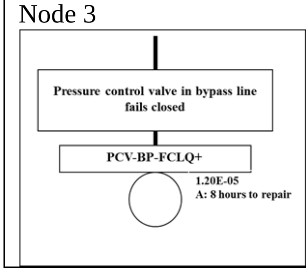
7.2.2.2. LPPP PPT Explosion

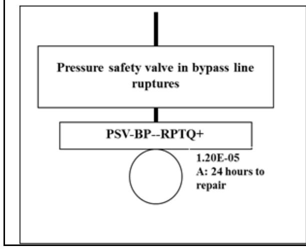
The following description of the Explosion in the Low Point Pump Pit (LPPP) in the Precipitate Pump Tank (PPT) is provided the DWPF Event Tree Report (Sarrack et al, 1995, Page 16):

> "Benzene vapor explosion is the-safety concern for the Precipitate Pump Tank (PPT) in the Low Point Pump Pit (LPPP). PPT is operated with a primary nitrogen gas purge to keep the oxygen concentration from reaching MOC. The primary nitrogen source.is the bulk nitrogen gas system; the backup nitrogen sources area bank of high pressure nitrogen cylinders and the local LPPP nitrogen tank supply. The backup system actuates automatically upon loss of primary purge supply. Instruments monitor oxygen concentration in the effluent stream from PPT which goes to the Process Vessel Vent. System (PWS). If the oxygen level gets too high, an outlet control valve closes automatically isolating the tank from the PWS, to allow nitrogen gas pressure to buildup in the vessel, thereby preventing leakage of air into the PPT."

The APET for the benzene vapor explosion in the PPT contains 4 nodes which could be impacted by the proposed performance measures. Table 7-2 contains a list of nodes and proposed changes to the probabilities associated with them that might be used to estimate how a nuclear chemical facility functioning with the recommended performance measures might have a reduced probability of the event. Table 7-2 also shows the sensitivity of this overall probability change for each potentially affected node.

Table 7-2 | Explosion in the Low Point Pump Pit Affected Nodes and Probability Changes

Node	**Source of data for probability and assumptions**	**Impact of performance measure on assumptions**	**Rationale**	**Revised probability estimate** **Percent Change of Overall Event Probability for Node (%)**
Node 1 	The source of the current failure probability is the Valve (control) motor operated fails closed, CMV-FC-C in the Savannah River Site Generic Database Development from 1993 (Blanton and Eide, 1993). The current value is 1.2E-5, which assumes a 3E-6H failure rate where H is 4 hours.	With the addition of Maintenance and Engineering Controls performance measures to ensure safety systems are maintained and controls are designed by the right subject matter experts, the pressure control valve may be less likely to fail closed.	Using the same rationale of increased maintenance and engineering programs described in the previous APET: a 50% to 75% reduction in component failure rates has been observed in system/facilities with successful predictive and/or precision maintenance program (Blanchard, 1996, Page 11), a 50% reduction in the failure rate might better represent the probability of this failure.	6E-6 1.49
Node 2 	The source of the current failure probability is the Safety/Relief Valve rupture (internal) SRV-RI-G in the Savannah River Site Generic Database Development from 1993 (Blanton and Eide, 1993). The current value is 1.2E-5, which assumes a 5E-7H failure rate where H is 24 hours.	With the addition of Maintenance and Engineering Controls performance measures to ensure safety systems are maintained and controls are designed by the right subject matter experts, the pressure safety valve may be less likely to rupture.	See above for the 50% guideline to reduce the failure rate for the pressure safety valve rupture.	6E-6 0.25
Node 3 	See Node 1 for a similar scenario.	See Node 1 for a similar scenario.	See Node 1 for a similar scenario.	6E-6 1.49

<table>
<tr>
<td>Node 4

</td>
<td>See Node 2 for a similar scenario.</td>
<td>See Node 2 for a similar scenario.</td>
<td>See Node 2 for a similar scenario.</td>
<td>6E-6
―――
0.25</td>
</tr>
</table>

With all potentially affected nodes included in the analysis, the new probability of the LPPP PPT explosion may be as low as 1.88E-6 per year. Without any of the additional considerations, the probability was 1.94E-6 per year. In total, this APET had 17 input nodes. Of these 17, 4 were modeled improved by the performance measures.

7.2.2.3. Benzene Explosion in the SPC

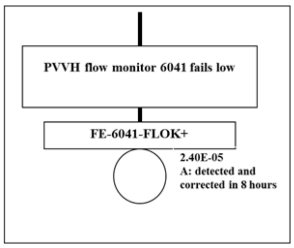
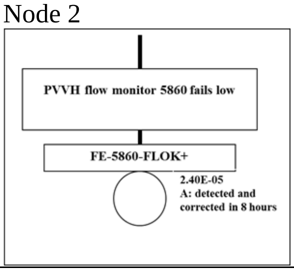
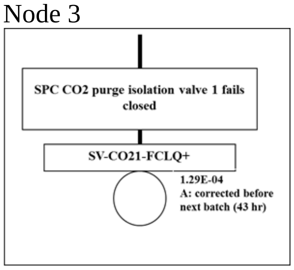
The following description of the benzene explosion in the Salt Processing Cell (SPC) (Sarrack et al, 1995, Page 18):

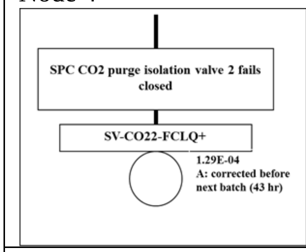
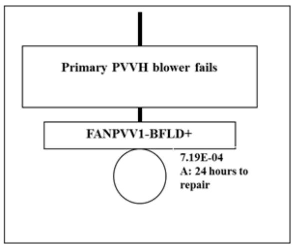
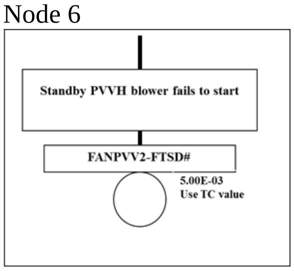
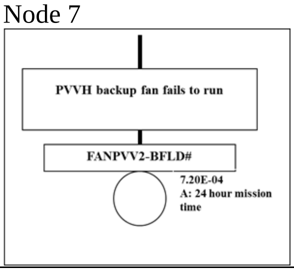
> “The Zone 1 ventilation system purges the Salt Processing Cell (SPC) which prevents the accumulation. of potentially flammable benzene vapor within the cell volume. Ventilation system failure with either SPC vessel over-pressurization, vessel overheating, or spill of waste solution into the SPC sump without pumping to the PR could result in benzene vapor concentrations reaching LFL within the SPC. Pressurization of process vessels in SPC is a safety response to detected high oxygen levels within, any of these vessels. However, this increases the risk of benzene vapor accumulation in the cell volume outside the vessels. While explosion prevention by inerting is the main concern within SPC vessels, the concern in the Process Vessel Vent Header (PVVH) is LFL (dilution) control. The off-gas ventilation from SPC, combines with the flow from CPC, thus diluting the benzene concentration in PVVH. If the PVVH flow gets too low, an automatic interlock closes two valves and isolates SPC from PVVH. This interlock also turn off CO2 supply pressure to SPC vessels. SPC vessels are protected from reaching

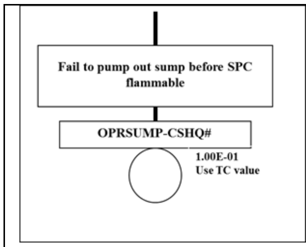
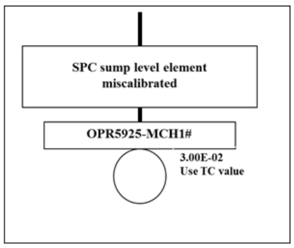
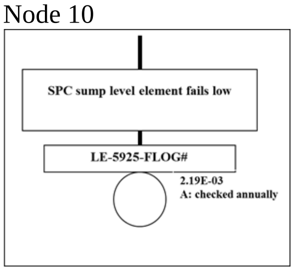
MOC by a nitrogen purge. Pressure interlocks stop the supply of steam to PR and OE and starts cooling water flow to these vessels. Since the seismic trigger interlock is designed to isolate the SPC from the PVVH and supply a constant flow of nitrogen to SPC vessels, the SPC Explosion seismic fault tree models benzene to always enter the cell following an earthquake. The fault tree concludes that if Zone 1 ventilation fails, a cell explosion occurs. SPC system boundaries include support systems, such as: Zone 1 -ventilation system components, instrument air system, cooling tower water system, normal and backup electric power systems, and the control instrumentation associated with the PVVH low flow interlock."

The APET for the benzene explosion in the SPC contains 10 nodes which could be impacted by the proposed performance measures. Table 7-3 contains the list of nodes and proposed changes to the probabilities associated with them that might be used to estimate how a nuclear chemical facility functioning with the recommended performance measures might have a reduced probability of the event. Table 7-3 also shows the sensitivity of this overall probability change for each potentially affected node.

Table 7-3 | Benzene Explosion in the Salt Processing Cell Affected Nodes and Probability Changes

Node	**Source of data for probability and assumptions**	**Impact of performance measure on assumptions**	**Rationale**	**Revised probability estimate** **Percent Change in Overall Event Probability for Node (%)**
Node 1 	The source of the current probability is the Flow Failure recommended value with a failure rate of 3.0E-6H where H is 8 hours in the Savannah River Site Generic Database Development from 1993 (Blanton and Eide, 1993).	With the addition of Maintenance and Engineering Controls performance measures to ensure safety systems are maintained and controls are designed by the right subject matter experts, the flow monitor may be less likely to fail.	According to the 1996 version of the Savannah River Site Generic Database Development document, a 50% to 75'% reduction in component failure rates has been observed in system/facilities with successful predictive and/or precision maintenance program (Blanchard, 1996 Page 11). We can therefore assume that with the increased engineering design protocol and addition of maintenance performance measures, we might model a reduction of 50% of the current failure rate.	1.2E-5 2.48
Node 2 	For details about Node 2, see Node 1 above.	For details about Node 2, see Node 1 above.	For details about Node 2, see Node 1 above.	1.2E-5 2.48
Node 3 	The source of the current probability is the valve (control) motor operated fails closed with a failure rate of 3.0E-6H where H is 43 hours in the Savannah River Site Generic Database	With the addition of Maintenance and Engineering Controls performance measures to ensure safety systems are maintained and controls are designed by the	With the addition of the new performance measures we might apply the 50% failure rate reduction proposed previously.	6.45E-5 2.48

	Development from 1993 (Blanton and Eide, 1993).	right subject matter experts, the purge isolation valve may be less likely to fail.		
Node 4 	For details about Node 4, see Node 3 above.	For details about Node 4, see Node 3 above.	For details about Node 4, see Node 3 above.	6.45E-5 2.48
Node 5 	The source of the current probability is the Fan/blower fails to run, MDF-FR-H in the Savannah River Site Generic Database Development from 1993 (Blanton and Eide, 1993). The current value is 7.19E-4, which assumes a 3E-5H failure rate where H is 24 hours.	With the addition of Maintenance and Engineering Controls performance measures to ensure safety systems are maintained and controls are designed by the right subject matter experts, the pressure control valve may be less likely to fail closed.	We might model the improvement to this node using the 50% reduction to the failure rate proposed previously.	3.6E-4 0.33
Node 6 	The source of the current probability is the Fan/blower fails to start, MDF-FS-H in the Savannah River Site Generic Database Development from 1993 (Blanton and Eide, 1993). The current value is 5.00E-3, which assumes the nominal failure rate of 5E-3.	With the addition of Maintenance and Engineering Controls performance measures to ensure safety systems are maintained and controls are designed by the right subject matter experts, standby blower may be less likely to fail to start.	Because we are using the nominal failure rate, we will not assume any reduction in probability for this node.	5E-3 0
Node 7 	Node 7 is similar to Node 5. See Node 5 above for more information about the backup fan failing to run.	Node 7 is similar to Node 5. See Node 5 above for more information about the backup fan failing to run.	Node 7 is similar to Node 5. See Node 5 above for more information about the backup fan failing to run.	3.6E-4 0.02
Node 8	The source for the current reading is the	With the addition of the engineering	The use of the nominal value (several	1.0E-02

	Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities from 1994, listed in Table 4 of that report (Benhardt et al, 1994). The current value is the high probability estimate for Failure to Respond to Compelling Signal.	controls metric to ensure nuisance alarms are not desensitizing operators, a reduction in probability for this node may be warranted.	competing signals), rather than the high value (many competing signals) is modeled.	10.0
Node 9 	The source for the current reading is the Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities from 1994, listed in Table 4 of that report (Benhardt et al, 1994). The current value is the high probability estimate for Miscalibration.	With the addition of the two operating procedures performance metrics, the sample analysis procedures should be current, accurate and effective and revised or developed using the right subject matter experts.	With these additional controls in mind, a reduction in probability for this node may be warranted. . The major contribution to this failure probability involves failure to use the calibration procedure, failure to use a checklist properly when using the procedure, an error of omission or commission during the calibration procedure, and failure of the operator to detect the error by comparing before and after instrument readings (Benhardt, 1994). The use of the nominal value (single person, operator check), rather than the high value (single person, no checks) is modeled.	5.0E-03 2.59
Node 10 	The source of the current probability is the Level Failure LST-FA-I in the Savannah River Site Generic Database Development from 1993 (Blanton and Eide, 1993). The current value is 2.19E-3, which assumes a 5.0E-7H and is checked annually. The hours input was 4,380 hrs.	With the addition of Maintenance and Engineering Controls performance measures to ensure safety systems are maintained and controls are designed by the right subject matter experts, the level element may be less likely to fail low.	We might reduce the failure rate associated with the level element similarly to the previous nodes by 50%.	1.1E-3 0.22

With all potentially affected nodes included in the analysis, the new probability of the SPC Explosion may be as low as 8.27E-5 per year. This compares favorably to the 1.08E-4 per year without the improvements. In total, this APET had 29 input nodes. Of these 29, 10 were modeled improved by the performance measures.

7.2.3. Results

The results of the application of the developed performance measures and their potential areas of improvement on the three select probabilistic risk assessments demonstrated a potential decrease in the probability of all three studied events. The three decreases are included in Table 7-4 below.

Table 7-4 | Percentage Change for each APET with Proposed Performance Measures

Event	Probability prior to performance measure considerations	Probability including performance measure considerations	Percentage decrease in probability
Steam explosion in the melter	1.82E-5	6.29E-8	93.3%
Explosion in LPPP PPT	1.94E-6	1.85E-6	3.09%
SPC Explosion	1.08E-4	8.27E-5	23.5%

Each of the analyzed events experienced a reduction in the probability of the event per year by applying reductions using the developed performance measures. The most useful performance measures for the reductions were the operating procedures measures and the maintenance procedures, both of which had strong ties to human error probability nodes in the event trees including failure to follow procedures, failure to perform tasks correctly, such as sample analysis and calibration of equipment. The engineering controls performance measures also had ties to many of the nodes, in particular those related to the reliability of equipment such as analyzers, flow monitors, isolation valves and pressure control valves, but at a pre-operational stage, so they were not directly impactful to the overall event probability. The hazards analysis performance measures are similar—they impact the development of controls, which reduce the probability, but were not represented by individual nodes as frequently.

The take away from this exercise is further illustration of the overall value of the proposed impactful performance measures to a nuclear chemical facility such as DWPF. Some of the proposed performance measures had a high impact on the overall probability of the event modeled. For example, the engineering controls and operating procedures measures nodes in the Steam Explosion in the Melter APET described above, modeled a change in the event probability up to 88%, demonstrating their impact at nuclear chemical facility. This exercise provided another method for analyzing the potential impact of a performance measure using probabilistic risk assessment. The methods used in this analysis could also benefit industry by providing a way to determine impact of performance measures where a probabilistic risk assessment is available.

7.3. Application of Performance Measures at DOE nuclear chemical facilities

The objective of 7.3 is to provide facilities with guidance for the implementation of these performance measures at a nuclear chemical facility.

7.3.1. Introduction

The performance measures recommended for application at nuclear chemical facilities were checked for quality by the subject matter expert review, and tested using a quantitative reduction in risk at a nuclear chemical facility using the DWPF Probabilistic Risk Assessment described in section 7.2. However, the specific application of these performance measures at a facility may provide some uncertainty or be the source of some questions. For instance, many of the recommended performance measures relate to getting the “right people” involved in the various processes, while this was deemed very important, it could be difficult to measure and monitor. Further, once the data is collected, it may be difficult to determine how to turn the data into a single metric, and how to determine the health of the system based on this metric. For instance, when collecting data about the involvement of subject matter experts in the hazard analysis, there may be multiple data points such as training and qualification records to ensure expectations for subject matter expertise are met, potential process metrics to track their involvement in the hazards analysis, and potentially self-assessment data to ensure the process metrics are trending in a positive direction. In order to effectively monitor this data, it may be necessary to combine these data points into a single metric. Further, it will be necessary to establish a baseline, a point that can be deemed “safe,” and a range of values for safe operation. In the SME involvement in the hazards analysis described above, a baseline would be required for training and qualification expectations, as well as the process metrics and self-assessment values. By definition, anything outside of this range would then be "unsafe" or veering in the direction of unsafe operating conditions. Baseline values may be site or process dependent, but some general guidelines are offered in this report.

This section resolves to answer these questions about the proposed performance measures and provide recommendations for measuring and monitoring the health of a nuclear chemical facility over time. For each performance measure, recommendations are provided for how the data could be collected, and developing a baseline and operating range.

7.3.2. Application Recommendations for Performance Measures at DOE Nuclear Chemical Facilities

The following sections describe the implementation of the Performance Measures at DOE Nuclear Chemical facilities.

7.3.2.1. Engineering Controls Performance Measures

Performance Measure: Pertinent SMEs involvement in process design and/or review changes

Data to be collected: The process of determining if the right people are involved in the process design or review changes could be accomplished in a few ways.

The first step in determining if the right people were involved in the process design and reviewing any potential changes to it would be determining what types of SMEs would be necessary to ensure that the process design or change review could be deemed safe, for example, what types and how many engineers, health and safety professionals, operators, etc. The next step would involve determining what training and qualifications are expected to be classified as an SME. This would entail developing official expectations on training and qualifications required and updating and maintaining these expectations at a set frequency.

Once expectations are set, the next step is to track the completion of the training and qualifications program by the SMEs. When all of the official expectations determined in the first step are met, SMEs must have concurrence on the process design or change review which could be documented. SME involvement in process design and/or reviewing changes can be tracked. The following methods could be used to track SME concurrence in process design or change reviews.

One method would be to develop a template for each process design or change review meeting and require the signature of the SME that meets each required area of expertise (e.g. nuclear safety, industrial hygiene, etc.). In this case, a document review performed at a designated interval could be used to verify that signatures were achieved on this template in all of the processes, the data would be:

1. Percentage of signatures collected per form—would have to be go/no-go

Another method would be a periodic self-assessments or independent assessments of the documentation of the design documents or change documents to collect information about the personnel involved in the development of these documents. The data associated with this method might include:

1. The number of documents analyzed
2. For each expertise, the number of authors or contributors associated with the documentation
3. Qualification/training of required reviewers established and accomplished

Either of these methods might also require the occasional review of technical qualifications of the participants, for instance, the qualifications of the particular signatories or participants in either method might be reviewed for a certain number of meetings or documents in a given year. The data collected for this analysis might include:

1. Areas of subject matter expertise with established training and qualification programs
2. Percentage of experts trained or qualified
3. Percentage of meetings which had trained/qualified attendees

Developing a Baseline: The baseline for these reviews to determine if the right experts were involved in the process design and to review proposed changes to the system would be the lowest percentage of participation at which the design or changes to it could be deemed safe and reliable. The goal would be to have 100% participation at all meetings. However, this might not be feasible. If participation is regularly low, an assessment may be required to determine which specialties are regularly missing from the documentation and work to resolve this issue.

Performance Measure: Percentage of operators and technical staff who are able to identify controls and believe that they understand their operations

Data to be collected: The percentage of operators and technical staff who are able to identify controls and believe that they understand their operations could be monitored using a self-assessment or survey of the operators and technical staff. This survey could be administered as a part of annual training (e.g. safety training, rad con training, etc.) and could include technical questions about the controls associated with a system and/or questions about the confidence of the operators and technical staff in their understanding. For example:

Technical question: Which of the following control(s) is/are associated with maintaining the containment of X:

(a) Elevated design of ammonia tank

(b) Pressure relief device

(c) Temperature control

(d) Vehicle barricade

Subjective question: Do you believe you understand the operation of the controls associated with X system?

(a) Yes

(b) No

The data collected for this measure would then be the percentage of operators and technical staff who responded either correctly to the technical question, or affirmatively to the subjective question during each assessment application.

1. Percentage of operators and technical staff who correctly responded to the technical question(s)
2. Percentage of operators and technical staff who responded affirmatively to the subjective question(s)

Developing a Baseline: The goal for the assessment of the operators and technical staff would be to have 100% be able to identify the important controls at their facility and respond affirmatively that they understand operation and control of the system and process. However, 100% may not be possible. A minimum level of technical understanding and affirmative responses would need to be determined, based on the highest percentage received during a time period of safe operation (no occurrences) and a dip below this could be a red flag for the safety of operating the system.

Performance Measure: Number of "nuisance alarms" or false alarms

Data to be collected: The data collected for this metric would be as follows:

1. The total alarms actuated during the prescribed time period
2. The number of alarms actuated during the prescribed time period labeled as false alarms or "nuisance alarms"

Recommended Calculations:

The percentage of actuated alarms that were "nuisance" or false alarms

Developing a Baseline: The baseline for the percentage of nuisance or false alarms would be set at a percentage which is deemed distracting or dangerous for operation of the process. The baseline could be developed by collecting 6 months of data and then establishing improvement strategies and goals.

7.3.2.2. Operating Procedures Performance Measures

Performance Measure: Number of operators or maintenance technicians who believe procedures are current, accurate, and effective

Data to be collected: The percentage of operators or maintenance technicians who believe procedures are current, accurate, and effective could be collected using an assessment with a question similar to the following:

Assessment questions:

Based on your experience with procedures, do you believe that operating procedure X is current and accurate (does the written procedure represent the procedure performed)?

Based on your experience with procedures, do you believe that operating procedure X is effective (does procedure X accomplish the task it is designed to accomplish)?

Based on your experience with procedures, do you believe that operating procedure X achieves the goal in the safest way?

The data would then be the percentage of operators and maintenance technicians who responded affirmatively to the questions in the prescribed time period. This data could also be trended over a longer timeframe, for instance years, and if the responses began trending down, it may be a sign that procedures are becoming outdated.

Developing a Baseline: The goal for the assessment of the operators and technical staff would be to have 100% respond affirmatively that operating procedures are current, accurate, and effective. However, 100% may not be achievable at the facility. A minimum percentage of responses would need to be determined, based on the highest percentage for safe operation, and a dip below or above this could be a red flag for the safety of operating the system. To achieve this baseline, data could be collected for a prescribed time period and a target improvement trend could be set to ensure the organization is staying on target for improvement.

Performance Measure: Pertinent SMEs involved in drafting procedures

Data to be collected: The process of determining if the right people are involved in drafting procedures is similar to the first performance measure discussed (SME involvement in process design and/or review changes) and could be accomplished in a few ways.

The first step in determining if the right people were involved in the development of operating procedures would be determining what types of SMEs would be necessary to ensure that the operating procedure could be deemed safe, accurate, and up to date, for example, what types and how many engineers, health and safety professionals, operators, etc. The next step would involve determining what training and qualifications are expected to be classified as an SME. This would involve developing official expectations on training and qualifications required and updating and maintaining these expectations at a set frequency.

Once expectations are set, the next step is to track the completion of the training and qualifications program by the SMEs. When all of the official expectations determined in the first step are met, SMEs must have concurrence on the operating procedure which could be documented. SME involvement in developing operating procedures can be tracked using the following methods.

One method would be to develop a template for each operating procedure development or change meeting and require the signature of the SME that meets each required area of expertise (e.g. nuclear safety, industrial hygiene, etc.). In this case, a document review performed at a designated interval could be used to verify that signatures were achieved on this template in all of the processes, the data would be:

2. Percentage of signatures collected per form—would have to be go/no-go

Another method would be a periodic self-assessments or independent assessments of the documentation of the operating procedures to collect information about the personnel involved in the development of these documents. The data associated with this method might include:

4. The number of documents analyzed
5. For each expertise, the number of authors or contributors associated with the documentation
6. Qualification/training of required reviewers established and accomplished

Either of these methods might also require the occasional review of technical qualifications of the participants, for instance, the qualifications of the particular signatories or participants in either method might be reviewed for a certain number of meetings or documents in a given year. The data collected for this analysis might include:

4. Areas of subject matter expertise with established training and qualification programs
5. Percentage of experts trained or qualified
6. Percentage of meetings which had trained/qualified attendees

Developing a Baseline: The baseline for these reviews to determine if the right experts were involved in the development and maintenance of operating procedures would be the lowest percentage of participation at which the operating procedure could be deemed safe and reliable. The goal would be to have 100% participation at all meetings. However, this might not be feasible. If participation is regularly low, an assessment may be required to determine which specialties are regularly missing from the documentation and work to resolve this issue.

7.3.2.3. Maintenance Performance Measure

Performance Measure: Amount of time the plant is in operation with any safety system in an inoperable or degraded condition

Data to be collected: The amount of time the plant is in operation with any safety system inoperable or in a degraded condition could be tracked in a few different ways:

The first method would be to monitor the amount of time spent in a limited condition of operation (LCO) (defined by the Atomic Energy Act as the lowest functional capability or performance levels of structures, systems, components, and their support systems required for normal safe operation of the plant) in a designated timeframe:

1. Percentage of time spent in an LCO during each year or quarter

The second method would be to monitor entry into a grace period (additional time allowed to complete the requirement before taking the required action of an LCO; does not exist for all systems):

2. Number of times a grace period is entered in a given year or quarter

The third method would be to monitor the amount of time the grace period is utilized during a designated timeframe, for instance, if a facility regularly gets to the end of the grace periods, this may be an indication of degraded safety conditions.

3. Percentage of grace period utilized during each entry into a grace period in a given time period

Developing a Baseline: The goal would be to minimize the amount of time that the plant is in operation in a grace period or LCO. A low percentage could be developed, based on the most successful and safe phases of operation data, over which a flag would be raised to the safety of the operation of the system. Additionally, improvement strategies could be developed and the baseline to the improvement track monitored to ensure compliance with the targeted trend.

7.3.2.4. Hazards Analysis Performance Measures

Performance Measure: Pertinent SME involvement in DSA development and maintenance

Data to be collected: The process of determining if the right people are involved in DSA development and maintenance is similar to the first performance measure discussed (SME involvement in process design and/or review changes) and could be accomplished in a few ways.

The first step in determining if the right people were involved in the DSA development and maintenance would be determining what types of SMEs would be necessary to ensure that the safety analysis could be deemed thorough, for example, what types and how many engineers, health and safety professionals, operators, etc. The next step would involve determining what training and qualifications are expected to be classified as an SME. This would involve developing official expectations on training and qualifications required and updating and maintaining these expectations at a set frequency.

Once expectations are set, the next step is to track the completion of the training and qualifications program by the SMEs. When all of the official expectations determined in the first step are met, SMEs must have concurrence on the operating procedure which could be documented. SME involvement in DSA development can be tracked using the following methods.

One method would be to develop a template for each safety documentation or hazards assessment meeting and require the signature of the SME that meets each required area of expertise (e.g. nuclear safety, industrial hygiene, etc.). In this case, a document review performed at a designated interval could be used to verify that signatures were achieved on this template in all of the processes, the data would be:

1. Percentage of signatures collected per form—would have to be go/no-go

Another method would be a periodic self-assessments or independent assessments of the DSA documentation to collect information about the personnel involved in the development of these documents. The data associated with this method might include:

1. The number of documents analyzed
2. For each expertise, the number of authors or contributors associated with the documentation
3. Qualification/training of required reviewers established and accomplished

Either of these methods might also require the occasional review of technical qualifications of the participants, for instance, the qualifications of the particular signatories or participants in either method might be reviewed for a certain number of meetings or documents in a given year. The data collected for this analysis might include:

1. Areas of subject matter expertise with established training and qualification programs

2. Percentage of experts trained or qualified
3. Percentage of meetings which had trained/qualified attendees

Developing a Baseline: The baseline for these reviews to determine if the right experts were involved in the development and maintenance of the DSA would be the lowest percentage of participation at which the facility operations could be deemed safe and reliable. The goal would be to have 100% participation at all meetings. However, this might not be feasible. If participation is regularly low, an assessment may be required to determine which specialties are regularly missing from the documentation and work to resolve this issue.

Performance Measure: Number of past due safety action items stemming from previous occurrences

Data to be collected: A couple of data sources for the measurement of past due safety action items stemming from previous occurrences could be achieved using the un-reviewed safety question (USQ) process. The USQ process occurs when a contractor identifies an unexpected situation that is inconsistent with the approved safety basis. A USQ is opened, but the contractor may be granted approval to continue operation while the USQ is resolved and corrective actions are put into place. This approval is called a justification for continued operation (JCO) and is limited to a pre-defined time period. An un-reviewed safety question determination (USQD) must be made to determine if there could be an effect on safe operation of the facility. This can be negative (no effect) or positive (potential effect). Three items related to the USQ process can be measured to determine if there are past due safety action items. These include:

1. Average length of time (in a given time period) before USQD is reached
2. The percentage of positive USQD corrective actions that are overdue
3. The percentage of JCOs that have to be extended—indicating that the corrective actions have not been completed in the allotted time

Developing a baseline: The baseline for the three data sources mentioned above should be developed by collecting available data (or, if there is none available, a year or two of data) and then establishing a target for improvement of these areas. Each reporting period, the data should be measured against the target to ensure improvement is occurring.

7.4. Considerations to Improve Safety and Efficiency of Operations at Nuclear Chemical Facilities

The previous chapters in this text have taken us through the development and finalization of a set of performance measures with the intent to improve safety and efficiency of operation at nuclear chemical facilities. However, the translation from the data collection to the development of theories about safety and efficiency of operation at nuclear chemical facilities to the list of final performance measures required the study to focus on a few key issues and theories about safety, leaving many other issues which were important in the data unexpressed. This section contains some recommendations for safety and efficiency of operations at nuclear chemical facilities that did not translate into the final performance measures.

Each of the themes that occurred with a high frequency in the chemical industry accident reports were reviewed in detail to develop ideas for areas of potential focus for thought regarding safety at a chemical or nuclear chemical facility. The following questions should be considered when evaluating the safety status of the facility or considering changes that might provide an opportunity to improve in some of these areas. These ideas can be tailored to the specific operations of the given industry.

If the answer to any of the questions is “no,” it may be an important step to consider the rationale for that answer and if there are any steps that should be taken to improve process safety in that particular area. Considering that the source of the data for these suggestions was an exhaustive database of accident reports, focusing in on the addressed areas may reduce the likelihood of a similar occurrence at your facility.

If the answer to these questions is “yes,” that suggestion has been considered at your facility, it is important to continue on and evaluate actions you are taking to address this consideration. If your facility is not currently addressing the issues raised in the questions, evaluate the improvement to the safety management program that could be achieved by implementing the industry ‘best practices’ that form the bases for the questions.

7.4.1. Design and Engineering Recommendations

Design and engineering issues had the highest frequency of occurrence in the studied accidents. Several performance measures for design and engineering are described in 7.3, and can be used to determine the health and safety of the facility with regards to its engineering controls and safety systems. Some observations were made in addition to these performance measures, and considerations related to these additional areas are detailed below.

- Are designs consistent with current industry standards (for instance, pressure vessel design should contemplate the most updated pressure vessel code of the American Society of Mechanical Engineers)?
- Do you enlist the assistance of a qualified team of people to perform peer review of engineering and design calculations for a new system or when making changes to an existing system.
- Does your engineering process evaluate scaling effects on the system when increasing the capacity or throughput of the processes?
- Do your safety-related systems implement the “multiple layers of protection” concept using both active (e.g. monitoring systems and alarms) and passive (e.g. containment) safety systems, as appropriate?

7.4.2. Standards Recommendations

Standards issues occurred frequently in the studied chemical industry accidents, but were significantly less frequent in the nuclear chemical facility occurrences, warranting their omission from the performance measure development phase. One potential reason for this difference could be the differences in regulation between the nuclear and chemical industries described in Chapter 2; nuclear facilities are highly regulated and regularly tracked and audited, while chemical facilities do not receive the same attention. Whatever the reason, there are some considerations any facility could take to improve safety and efficiency of operations with regard to standards:

- Do you regularly monitor the issuance and modification of technical and safety standards applicable to your facility?
- When compliance audits are performed, do you develop corrective actions and work to implement changes where they are deemed necessary?
- Do you participate in community planning; e.g., zoning laws and local emergency response plans can benefit from participation and information sharing by the chemical facilities in the community?

7.4.3. Process Hazard Analysis Recommendations

Two performance measures were developed to help measure the health and safety status of the facility hazard analysis. However, the additional considerations below may provide areas for improvement of this process and its associated documentation.

- Is your Process Hazard Analysis updated regularly, especially when changes are made to a process or facility (at a minimum, the PHA should be updated every 5 years, as required by OSHA)?
- Have you enlisted the assistance of a diverse team of experts when performing or updating the PHA to maximize the recognition of potentially hazardous scenarios?

7.4.4. Emergency Planning and Response Recommendations

Emergency Planning and Response was one of the most common issues identified in the analysis of the chemical industry accidents but performance measures related to this area were continuously ranked as the least practical and the least effective for determining the health and safety status of a facility by the SMEs surveyed. In the chemical industry accident reports studied, emergency responders made up a large percentage of the fatalities and severe injuries associated with the accident. The SMEs interviewed frequently commented on the available resources on site for emergency response, however, some sites have agreements with the local emergency responders in which they will provide on-site assistance if necessary; and this area might warrant a closer look. In addition to the research from this study about emergency planning and response, the DNFSB produced recommendation DNFSB 2014-1- Emergency Preparedness and Response in 2014. In this recommendation, DNFSB observed the "inability of sites with defense nuclear facilities to consistently demonstrate fundamental attributes of a sound emergency preparedness and response program, e.g., adequately resourced emergency preparedness and response programs and proper planning and training for emergencies" (DNFSB, 2014). As such, the following considerations related to emergency planning and response may be helpful in improving safety and efficiency of operations at a nuclear chemical facility.

- Has your facility recently reached out to emergency responders in the community to maximize effectiveness and communication?
- Does your facility have a means to ensure that adequate information about hazards present at the facility is available to emergency response teams?

- Have you developed and do you regularly update your facility's plan for emergency response, and run drills that involve the facility employees?

7.4.5. Hazard Recognition Recommendations

Hazard recognition was another area, similar to standards, which was more prevalent in the chemical industry accidents than the nuclear chemical facility accidents. Some additional considerations about hazard recognition are listed below:

- Are your employees thoroughly familiar with the process hazard documentation, as well as process safety information for the facility through formal and informal training programs?
- Are hazards clearly identified on operating procedures (for example, if a particular hazardous chemical is used in a process, include an attachment of the MSDS)?
- Do your procedure revision and design change processes encourage employees to participate in work planning and controls and use their operating and/or maintenance expertise to identify additional hazards and improve the process?

7.4.6. Observations for Regulators and Safety Oversight Organizations

In the process of completing this analysis, a few additional observations were made which could potentially improve safety in the chemical industry, and could also be applicable to other industries. These are ideas for regulators and safety oversight organizations to evaluate for implementation as they continuously improve their processes:

- Does your organization develop and release safety bulletin-type information regarding accidents or groups of accidents under your purview?
- Do your incident reporting procedures and accident analysis processes use a consistent set of Key Issues (like the major PSM topics) to facilitate monitoring of trends in these accidents?
- Do you revise your standards/processes, as necessary, when new guidance that could improve safety is released by industry groups, or when new technology or information becomes available through other sources, such as lessons learned from accidents?
- Do your oversight processes ensure standards are being implemented and followed at the required facilities and follow up as necessary on issues discovered during this process?

7.4.7. Development of Performance Measures for Areas Screened Less Impactful

The previous sections provide a starting point for developing measures for those areas deemed impactful through subject matter expert elicitation and the exercise with the DWPF PRA. However, the data was derived from accident analysis, and all performance measures developed were based on high impact issues from the accidents. All developed performance measures could have an impact on the safety of a nuclear chemical facility, and it is up to the facility to choose a list of measures that would be most effective given the unique set of operating conditions. The following paragraphs provide discussion on implementing the performance measures deemed less impactful by the SMEs.

The Engineering Controls performance measure that was considered less impactful by the SMEs and the PRA exercise was the amount of time in between inspections and tests of safety systems. To collect this data, the facility would first need to determine which systems constitute the safety systems described herein. In a DOE facility, these might be defined by safety significant or safety class systems. The facilities have a detailed schedule of inspections and tests, the completion of which are tracked. The data for this performance measure could include a percentage of these inspections or tests that are overdue during a given time period, and the time that has lapsed since the previous inspection. A baseline for this metric could be determined by comparing the industry standard inspections frequency with the actual frequency measured on the site, on a system by system basis.

The Operating Procedures performance measure that was considered less impactful by the SMEs and the PRA exercise was the percentage of procedures reviewed for content in a year. Data collection for this metric would include the total number of procedures, and the percentage of those that were reviewed in a given time period, in this case, one year. Another aspect of this data source might require review by specific SMEs, which is tied to SME involvement in drafting procedures, a measure described in Section 7.3.2. A baseline for this measure would be the minimum percentage of procedures reviewed in the time period to ensure safe and efficient operations. In an ideal setting, all active procedures would be reviewed on a frequent basis. It might also be useful in procedure review to establish improvement goals and targets for procedure review and measure the accomplishment of these targets.

In the area of Maintenance, there were two performance measures deemed less impactful by SME review and the PRA exercise. The number of past due maintenance requests as a percentage of total maintenance requests is a way to measure the overall maintenance backlog at a facility. The data required for this measure would be the number of maintenance requests that went past their scheduled due date in the maintenance tracking system and the overall number of maintenance requests accomplished during the same time period. The goal for this measure would be to have 100% of maintenance accomplished within the scheduled time period. However, this goal may not be practical, and it would be necessary to set improvement goals and targets and monitor the trajectory required to accomplish these goals.

The second Maintenance measure, the percentage of all safety systems and safety controls planned maintenance accomplished is similar to the past due maintenance requests, but focusing on safety systems. The first step in monitoring this area would be the development of the list of safety systems to be included; for instance, at a DOE facility, these might include Safety Class and Safety Significant systems. These systems would need to be separated in the maintenance tracking system, and the number of maintenance requests on these systems that are past due would need to be measured in a predetermined time period as well as the overall number of maintenance requests on safety systems. The goal would be to accomplish 100% of the safety systems maintenance within the scheduled time period. However, this goal may not be practical, and it would be necessary to set improvement goals and targets and monitor the trajectory required to accomplish these goals.

Two Hazards Analysis performance measures were determined to be less impactful by the SMEs and the PRA exercise. The first of these was the percentage of operators and/or maintenance technicians with formal training on the Documented Safety Analysis (DSA). The first step in this process would be to determine whether or not formal training of operators and maintenance technicians covers the safety basis for the facility, and in particular, the DSA. If it currently does not, the development of such a course would be required. Once a course is either verified or established, the data for this measure would include the training records for the operators and maintenance technicians who completed the course and are up to date on the training requirement. The goal would be to have 100% of operators and maintenance technicians receive and maintain formal training on the DSA. In order to achieve this goal, targets could be set for each year until completion and the achievement of these targets tracked.

The number of operations and maintenance personnel involved in DSA development and maintenance is similar to pertinent SME involvement in DSA development described in 7.3.2. Once expectations for operations and maintenance personnel involvement are set, there are several options for tracking their participation in DSA development and maintenance. One method would be to develop a template for each safety documentation or hazards assessment meeting and require the signature of the operator or maintenance technician that meets each required area of expertise. In this case, a document review performed at a designated interval could be used to verify that signatures were achieved on this template in all of the processes, the data would be the percentage of signatures collected per form—and would have to be go/no-go. The site could also perform a periodic self-assessments or independent assessments of the DSA documentation to collect information about the personnel involved in the development of these documents. The data associated with this method might include the number of documents analyzed and the number of signoffs by operators or maintenance technicians. The baseline for these reviews to determine if operators and maintenance technicians were involved in the development and maintenance of the DSA would be the lowest percentage of participation at which the facility operations could be deemed safe and reliable. The goal would be to have 100% participation at all meetings. However, this might not be feasible. If participation is regularly low, an assessment may be required to determine which specialties are regularly missing from the documentation and work to resolve this issue.

As discussed in Section 7.4.4, none of the Emergency Planning and Response performance measures were deemed impactful by SME review or through the quantitative PRA exercise. However, these performance measures were developed due to the high frequency of emergency response issues in analyzed chemical industry accidents. The first recommended performance measure is the number of local emergency responders trained on the facility hazards response. This performance measure is designed to provide information on the training of offsite responders, such as city or county responders, and their familiarity with the site hazards and appropriate response actions. The data for this measure would be training records for the surrounding emergency responders, within a predetermined geographical area (defined in the site Emergency Response Plan). Data would include the total number of responders and the number with up to date training on site emergency response. The goal would be to have 100% participation in site training by any emergency responder that might be asked to enter the site in the case of an emergency. This goal may require a set of annual targets, and the site should ensure it is meeting the targets each year until the goal is achieved.

The second emergency planning and response performance measure is the Number of emergency drills performed in a time period vs. number scheduled (or required). This measure is getting at the timely performance of drills. The data to be collected would include the number of drills scheduled, the number of drills required, and the number of drills successfully accomplished during a prescribed time period. The goal would be for the site to be completing 100% of the required drills, and 100% of the scheduled drills. If these numbers are not the same, a first target would be to schedule 100% of the drills required. Once this target is met, targets would include increments of increased drills accomplished until all scheduled drills were accomplished.

The last emergency planning performance measure is the number of workers in the facility who believe that they can execute their responsibilities in the case of an emergency. Data for this measure would be accomplished by survey, with questioning similar to this example: Do you believe that you understand your responsibilities in an emergency? Do you believe that you are capable of fulfilling these responsibilities? The goal for this measure would be to have 100% of respondents affirm both of these areas. If the percentage of affirmative responses is low, targets could be set to achieve this goal and their accomplishment tracked to demonstrate improvement.

7.4.8. Considerations Conclusions

The results of analyzing the data contained in the chemical industry accident reports and nuclear chemical facility occurrence reports identified several themes that can be used to develop a better understanding of chemical industry accidents and aid in continuous improvement of safety management programs; thus, potentially preventing future accidents from occurring or reducing their impacts. From the results of this analysis, performance measures were developed and vetted to use as leading indicators of process safety, and implementation guidelines were provided for both the most impactful and less impactful measures. Due to the nature of the list of performance measures, some important themes from the accident analysis were left out. Therefore, a list of recommended considerations was developed to encourage the facility managers to think about some other themes and issues at their facilities.

The analysis that resulted in these considerations evaluated experience from a broad spectrum of facilities in the chemical industry and nuclear chemical facilities from the DOE and NRC. Facilities, companies and industry groups may be more interested in experience specific to their portions of either industry.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1. Introduction

The subsequent chapters have provided the details of the accident analysis, grounded theory development, and performance measure development and vetting. The goal of Chapter 8 is to provide conclusory remarks on this research. Chapter 8 will reiterate the accomplishments of this work and provide ideas for the continuation of this research and performance of future work.

8.2. Conclusions

The rich database available in the chemical industry accident reports and occurrence reports from nuclear chemical facilities operated by the DOE and NRC contains valuable organizational learning information that can be used to help improve the safety and efficiency of operations at nuclear chemical facilities. The work presented in this study illustrated the usefulness of these reports through the semi-quantitative analysis of textual data: key issues and content. A content analysis of these reports was performed to highlight the common causes and themes of accidents in the chemical industry and occurrences at operating nuclear chemical facilities. The codes and memos marking these issues were used to develop grounded theory about safety at nuclear chemical facilities. One theory was developed for each of the predominant issues from the accident reports, 29 in total.

Once the theories were developed, a set of leading performance measures was postulated relating the issue, the most commonly associated codes from the content analysis, and the theory. These leading performance measures were reviewed by a set of industry subject matter experts through two iterations to revise wording and highlight the most impactful performance measures that were both practical and effective for a nuclear chemical facility. The subject matter experts narrowed the list to 17 performance measures and selected 8 performance measures that were considered the most impactful to safety and efficiency of operations at a nuclear chemical facility.

The list of performance measures follows, where the bolded measures are the most impactful:

- Engineering Controls:
    - **Pertinent subject matter expert involvement in process design and/or review changes**
    - **Percentage of operators and technical staff who are able to identify controls and believe that they understand their operation**
    - Amount of time in between inspections or tests of safety systems
    - **Number of nuisance alarms or false alarms vs. number of valid alarms**
- Operating Procedures
    - Percentage of procedures reviewed for content in a year
    - **Number of operators or maintenance technicians who believe that procedures are current, accurate, and effective (by survey)**
    - **Pertinent SMEs involved in drafting procedures**
- Maintenance
    - Percentage of all safety systems and safety controls planned maintenance accomplished
    - Number of past due maintenance requests as a percentage of total maintenance requests

- **Amount of time the plant is in operation with any safety system in an inoperable or degraded condition**

- Hazards Analysis
  - Percentage of operators and/or maintenance techs who have formal training on the Documented Safety Analysis (DSA)
  - **Pertinent subject matter expert involvement in the DSA development and maintenance**
  - Number of operations and maintenance personnel involved in DSA development and maintenance
  - **Number of past due safety action items vs. total number of safety action items stemming from previous occurrences**
- Emergency Planning
  - Number of local (county or city) Emergency Responders trained in facility (e.g. chemical or radiological) hazards and response
  - Number of emergency drills performed in a time period vs. number scheduled (or required)
  - Number of workers in an operating facility who believe that they can execute their responsibilities in the case of an emergency (by survey)

A second exercise to determine the impact of the performance measures was conducted using a probabilistic risk assessment for an operational nuclear chemical facility. The performance measures were matched up to nodes in several accident progression event trees that they could impact and the nodes were then modeled with a reduction in the failure or error probability. The quantitative exercise provided an alternative way to measure the potential impact of the performance measures at a nuclear chemical facility, with maintenance, operating procedures, and engineering controls performance measures being the most impactful to the selected events.

Guidance was provided for the 18 performance measures to assist in implementing the performance measures at a facility. This guidance included a discussion about the data required, including a discussion of additional setup requirements (such as additional training or documentation) where they might not exist. Guidance was also provided to assist in setting a baseline for each of the performance measures. The next phase of this process will involve piloting the performance measures at nuclear chemical facilities. This is discussed further in Section 8.3.

The performance measures resulting from this analysis, and subsequent ideas presented for improvement actions, can be used by facilities, companies, and industry groups—coupled with their own specific trend information—to evaluate and prioritize process safety at targeted nuclear chemical facilities and nuclear and chemical facilities, in general, to improve process safety and efficiency of operations.

The results of analyzing data contained in the chemical industry accident reports identified several theories that can be used to develop a better understanding of chemical industry accidents and nuclear chemical facility occurrences and aid in continuous improvement of safety management programs; thus, potentially preventing future accidents from occurring, or reducing their impacts. From the results of this analysis, several performance measures were presented which could be applied as leading indicators of process safety health at a nuclear chemical facility. When tracked, these performance measures could provide a leading indication of degraded safety conditions which may prevent an occurrence or accident from occurring. Further, these performance measures have been shown to be practical and effective for implementation at a nuclear chemical facility, and to have a quantitative reduction in risk for such a facility. The application of these performance measures at nuclear chemical facilities in the DOE complex was also discussed. The study presented measurable quantities and discussed the development of the recommended metric, as well as guidance for creating a baseline to determine the health of the process.

Further guidance and recommendations for safety not represented in performance measures was also related. The analysis related in this study evaluated experience from a broad spectrum of facilities in the chemical industry and nuclear industry. Facilities, companies and industry groups may be more interested in experience specific to their portions of the industry. The categorization scheme in this study, which uses industry-standard terminology derived from the OSHA PSM Guide, and the facility-specific CSB and DOE accident/occurrence database, can be used as a starting point, or example, for future industry-specific studies, or studies about a specific industry issue.

If applied as recommended, it is the hope of the authors that these performance measures will provide a leading indicator of unsafe operating conditions before an accident occurs. Considering that the source of the data for these performance measures and recommendations was an exhaustive database of accident reports, using the performance measures and focusing in on the addressed areas may reduce the likelihood of a similar occurrence at similar facilities.

8.3. Future Work

The research study that has been presented in this dissertation has elicited many thoughts for future work, both using the methods described in this study, and work on safety at nuclear chemical facilities.

Continuing the process of implementing the performance measures at nuclear chemical facilities will require piloting the recommended measures at several facilities. The first step in this process will be to work with the facilities to tailor the performance measures to the specifics of their operation, and then to assist in developing the programs to track the data. Data collection over several years will provide feedback necessary to make improvements before the rollout of the performance measures will be final.

The content analysis methodology used in this study has already been used in various alternate projects at Vanderbilt University. For instance, content analysis has been used to extract theories out of comments from an expert elicitation about fuel cycle preferences. There have also been discussions about applying this methodology to reviewing documents from other data sources to develop theories. The Electric Power Research Institute has expressed an interest in using a similar content analysis methodology to extract data from public comments on their reports to develop theories and themes in the data. Other industry groups, such as the Defense Nuclear Facilities Safety Board have also expressed an interest in using the methodology to assess report text.

There are many other potential sources of data that could be analyzed to provide insights regarding safety in the nuclear industry. There is data available to analyze accidents from all types of fuel cycle facilities, from mining and milling to long term storage and disposal. This data could be similarly used to develop theories about safety at any type of facility at any stage of the fuel cycle process, and eventually to develop performance measures similar to those developed in this study. In addition to mining the operating histories mentioned above using content analysis, there is the potential to perform a scraping analysis of these reports to determine the safety temperature of a specific industry, company, or facility. Additionally, web scraping analysis using the coding structure as a basis for the search, could increase the breadth of data covered and provide a more global look at process safety.

This work has also opened up the potential of working with the chemical industry, to provide feedback about accident conditions and lessons learned from a larger collection of accidents than those chosen for this study. In fact, the chemical industry accident analysis provided a list of recommendations that could apply to a chemical facility as well as the targeted nuclear chemical facilities. These recommendations could be expanded and broadcast to the chemical industry, or be reworked to develop a list of potential performance indicators that chemical facilities might use to improve safety and efficiency of operations.

Further work could also be done in studying nuclear chemical facilities. There are a host of international accidents and studies from the American Chemistry Council and the American Institute of Chemical Engineers available to study for the chemical aspects of operations, as well as many international nuclear chemical facilities with operating histories. Additionally, OSHA has a record of reportable accidents that goes back many years. Mining this data, if incident histories from these sources were available, could provide a tailored set of performance measures that could be used to improve safety and efficiency of operations at such facilities.

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APPENDIX A

CODING NOTES FOR THE CONTENT ANALYSIS

The contents of this Appendix are the coding notes used during the coding process to memo issues that were associated with each code.

Coding Notes

I. Hazards
    a. Hazard Recognition (PSM derived)
        1. HR1- Employees not made aware of hazards
        2. HR2- Hazards in design not understood
        3. HR3- Local potentially impacted people not aware of facility hazards
        4. HR4- No system or inadequate system to control hazards
        5. HR5- Hazard understood but not lessened
    b. Process Hazard Analysis (PSM)
        1. PHA1- Risks associated with the process not well analyzed
        2. PHA2- PHA inadequate
        3. PHA3- PHA does not involve literature review
        4. PHA4- PHA results not used
        5. PHA5- PHA process not defined
        6. PHA6- PHA requires revision or out of date
        7. PHA7- No PHA performed
        8. PHA8- PHA team not qualified to perform review
II. Standards
    a. Standards (Not PSM)
        1. ST1- Guidance for review of facility is insufficient
        2. ST2- Standards are not implemented at facility
        3. ST8- Standard not applied consistently throughout facility operations and facilities
        4. ST14- Standard limits occurrence

ii. Recognition
    1. ST10- Design standards not recognized or understood
iii. Implementation
    1. ST6- Facility or building siting
iv. Oversight
    1. ST11- Fire protection organizations do not monitor adherence to fire codes and standards
v. LTA
    1. ST3- Standards do not address all relevant issues
    2. ST4- Standards are not up to date
    3. ST7- Standard does not apply to a facility but should
    4. ST9- Standard does not exist
vi. Enforcement
    1. ST5- Standards not well enforced
    2. ST12- No inspections to ensure implementation
    3. ST13- No actions taken from enforcement

III. Safety Management
  a. Pre-Startup Safety Review (PSM)
    i. Performed before new or modified facilities
      1. PSSR1- Confirmation of safety systems performed LTA
      2. PSSR2- PSSR staff not experienced or knowledgeable
      3. PSSR3- Not signed off on
      4. PSSR4- Accident occurs during PSSR
    ii. Confirms safety
  b. Incident Investigation (PSM)
      1. II4- Not timely in investigation and communication
    ii. Previous incidents investigated
      1. II1- Previous accidents were ignored
      2. II5- Other facility incidents not looked into
      3. II6- Investigations into incidents were not thorough
    iii. Lessons learned collected
      1. II2- Lessons learned applied to new situations
    iv. Actions based on incident investigation taken
      1. II3- Actions taken based on investigation
      2. II7- Actions and recommendations are not thorough
  c. Process Safety Information (PSM)
      1. PSI1- PSI not available to relevant people
      2. PSI2- PSI not used in design
      3. PSI3- PSI not comprehensive
      4. PSI4- PSI out of date

ii. Written PSI compiled before PHA
iii. PSI provided to employer and employees
iv. PSI Complete

d. Compliance Audits (PSM)
1. COM1- Audits not timely
2. COM2- Recommendations from audit not utilized
3. COM3- Audit fails to address issue
4. COM4- Audits not performed by knowledgeable people
5. COM5- No program for audits exists

IV. Maintenance and Operations

a. Hot Work Permitting (PSM)
i. HW1- Flammable conditions inside a container
ii. HW2- Permits signed and checked
iii. HW3- Lack of controls for HW
iv. Permit issued
v. Permit complete

b. Mechanical Integrity (PSM)
1. MI1- Inoperable equipment
2. MI2- Lack of preventative maintenance program
3. MI3- Equipment issues caused by accident worsened accident conditions
4. MI8- Corrosion or degradation of materials

ii. Written procedures established
1. MI5- No MI procedures in place

iii. Employees trained in maintenance

iv. Inspections and tests performed and documented
1. MI4- Inspections and tests performed after the fact
2. MI7- Inspections and tests too infrequent
3. MI9- Lack of inspection plans
4. MI11- Inspections and tests did not find issues
5. MI12- No inspections performed

v. Deficiencies corrected in safe and timely manor
1. MI6- Equipment repeatedly causes issues
2. MI10- Deficiencies corrected in timely manner

vi. Equipment checked prior to startup
1. MI13- Equipment or conditions not checked before startup

vii. Counterfeit materials

c. Management of Change (PSM)
1. MOC1: Shift turnover changes
2. MOC2- reconfiguration without instructions

3. MOC4- incorrect characterization of big change as subtle change
4. MOC5- Prompt MOC process
5. MOC6- Change effects not fully understood
6. MOC9- MOC review not performed

ii. Written MOC procedures established

1. MOC7- Procedures not established

iii. Procedures altered in consideration of change

1. MOC8- Procedures adjusted with changes

iv. Employees affected or involved informed and trained

1. MOC3- Employees informed of changes

d. Maintenance (Not PSM)

1. MA6- Inconsistent staffing

ii. Conduct of Maintenance LTA

iii. Maintenance Planning

1. MA-1: Maintenance not alerted of issue
2. MA-2 Maintenance software issues
3. MA-3 Maintenance plan is LTA
4. MA4- Performance of maintenance LTA
5. MA5- Housekeeping is LTA
6. MA6- Communication about maintenance tasks
7. MA7- Maintenance spending
8. MA8- Endangerment of maintenance workers

iv. Housekeeping

e. Operating Procedures (PSM)

1. OP1- Inadvertent addition of material not in procedure
2. OP2- Procedure does not contain clear instructions for a part of the process
3. OP3- Procedure not followed by operators
4. OP5- No procedure for abnormal conditions
5. OP6- Procedure does not contain PSI
6. OP7- Procedure includes equipment no longer in service or obsolete
7. OP8- Inconsistent procedures used by different operators
8. OP9- Revisions to operating procedures
9. OP10- Procedures not analyzed for safety

ii. Written Clearly and Concisely

1. OP4- Procedures rely on memory of facility workers and are not written
2. OP11- No written procedure

iii. Accessible to Employees

iv. Reviewed and Updated as Necessary

V. Design and Engineering (Not PSM)

a. Engineering Controls

1. EC1- System does not contain design features necessary for safe operation
2. EC2- Physical failure due to underdesign
3. EC3- Failure to control equipment
4. EC4- Materials or equipment design issues
5. EC5- Represented need for more engineer participation in design or process
6. EC6- Design drawings or information not complete
7. EC7- System to correct design deficiencies
8. EC8- Design hazard recognition
9. EC9- System not installed according to design or other requirements
10. EC10- Engineers or professionals participation in design process and knowledge of design standards
11. EC11- Scale up issues
12. EC12- Computer Controls
13. EC13- Building siting
14. EC14- Manufacturing defect

b. Safety Systems

1. SS1- Failure to wear PPE
2. SS2- Lack of remote equipment for process safety
3. SS3- Ventilation system insufficient
4. SS4- Failure of a backup safety system (cooling)
5. SS5- Lack of controls
6. SS6- Lack of alarm system
7. SS7- Reliability of safety controls
8. SS8- Nuissance alarms or desensitization to alarms
9. SS9- Pressure relief devices
10. SS10- Fire protection systems
11. SS11- Vehicle controls
12. SS12- Emergency lights
13. SS13- Personnel safety equipment (safety showers)

VI. Human Factors

a. Contractors (PSM)

1. CON1- Poor communication between contractors and operators
2. CON2- Contractor understanding of process safety
3. CON3- Unauthorized contractor work

ii. Contractors Informed of Potential Hazards
iii. Illness and Injury Log Maintained
iv. Contractor Employees Familiar with PSI and Emergency Protocol
v. Contractors Document Training

b. Training (PSM)
    1. TR1- Employees not trained in use of maintenance requests or maintenance
    2. TR2- Training lacks process safety information (use of cautions and warnings, equipment purposes etc)
    3. TR4- MOC training
    4. TR5- Training is largely informal and may not cover all situations
    5. TR6- Training not offered with enough frequency
    6. TR7- Lack of training records
    7. TR8- No training offered on a particular piece of equipment or process
    8. TR9- Training not well planned or designed
    9. TR10- Inspector training for compliance
    10. TR11- Simulation training or training methods

ii. All Employees Trained
iii. Refresher Training
    1. TR3- Refresher training provided for hazards
iv. Training Recorded and Verified
v. Emergency Crews Trained
    1. ERT1- Emergency response crews participate in training with real drills and process information
vi. 911 Personnel Trained

c. Management Oversight (Not PSM)
    1. MO1- Managers on site
    2. MO2- Manager knowledge of process and design
    3. MO3- Manager sign off and approve process
    4. MO4- Management implements process safety actions
    5. MO5- Managers lack safety concern

d. Employee Participation (PSM)
    1. EP1- Employees participate in incident investigation and planning of actions to correct incident conditions
    2. EP2- Employees participate in work planning

ii. Employer Plan of Action
iii. Employees consulted in hazard analysis

VII. Emergency Planning and Response (PSM)

a. Emergency Planning (Broken Down from PSM)

i. Plan Established
    1. EPP1a- Lack of emergency plan
    2. EPP1b- Drills relating to plan performed
    3. EPP1c- Plan clarifies roles and responsibilities
ii. Employees Aware of Plan
iii. Plan Followed in Emergency
    1. EPP3a- Failure to account for all personnel
    2. EPP3b- Failure to sound alarm system
    3. EPP3c- Community and other responders aware of and involved in emergency planning
    4. EPP3d- Failure to follow plan
    5. EPP3e- Information for response and treatment of injured

b. Response (Broken Down from PSM)
    1. ERR1- Failure to establish safety of environment at facility
    2. ERR4- Community evacuation issues
    3. ERR5- Communication issues with local emergency response
    4. ERR6- Assistance necessary from additional emergency crews
    5. ERR10- Desire to help others overwhelms training or response instinct

ii. Point Person Available
    1. ERR7- No one assigned to point person
iii. Emergency Responders
    1. ERR2- Offsite responders participate in drills
    2. ERR3- Site information shared with emergency responders
    3. ERR8- Offsite crews injured
    4. ERR9- Insufficient resources

VIII. Other

a. Safety Culture (Not PSM—DOE G 450.4-1C)

i. Leadership
    1. L1- Risk informed decision making
    2. L2- Staff recruitment, selection, retention, development
    3. L3- Management engagement and time in field
    4. L4- Open communication and environment free from retribution
    5. L5- Demonstrated Safety Leadership
    6. L6- Clear expectations and accountability
ii. Employee Engagement
    1. EE1: Personal commitment to safety—did not heed caution statements, did not perform work in accordance to standards
    2. EE2- Mindful of hazards and controls
    3. EE3- Participation in work planning and controls

4. EE4- Teamwork and Mutual Respect

iii. Organizational Learning

1. OL1- Previous accidents were ignored
2. OL2- Effective resolution of reported problems
3. OL3- Credibility, trust and reporting errors and problems
4. OL4- Use of operational experience
5. OL5- Questioning attitude
6. OL6- Performance monitoring through multiple means

APPENDIX B

VANDERBILT INTERNAL REVIEW BOARD EXEMPTION

The following Appendix contains the Vanderbilt University Internal Review Board Exemption Letter for the Subject Matter Expert Survey portion of this analysis.

Vanderbilt University
Institutional Review Board
504 Oxford House Nashville, Tennessee 37232-4315
(615) 322-2918 Fax: (615) 343-2648
www.mc.vanderbilt.edu/irb

August 19, 2015

Lyndsey Fyffe, MS
Civil&Environ Engr

RE: IRB# 151251 "Nuclear Safety Subject Matter Expert Elicitation for Improvement of Performance Measures"

Dear Lyndsey Fyffe, MS:

A designee of the Institutional Review Board reviewed the Request for Exemption application identified above. It was determined the study poses minimal risk to participants. This study meets 45 CFR 46.101 (b) category (2) for Exempt Review.

Any changes to this proposal that may alter its exempt status should be presented to the IRB for approval prior to implementation of the changes. In accordance with IRB Policy III.C, amendments will be accepted up to one year from the date of approval. If such changes are requested beyond this time frame, submission of a new proposal is required.

Please note, the federal regulations do not require updates to key study personnel for exempt research. As such, effective ***October 15, 2012***, the Vanderbilt Human Research Protection Program will no longer ask for OR require administrative amendments to update KSP for those studies that qualify for an exemption under any of the categories for 45 CFR 46.101(b) (1-6).

DATE OF IRB APPROVAL: August 19, 2015

Sincerely,

James G. Arrington, BA, CIP, Regulatory Compliance Analyst IV
Behavioral Sciences Committee
JGA/jga
Electronic Signature: James G Arrington/VUMC/Vanderbilt : (DA940DE3F527973C92620ED132FBA34D)
Signed On: 08/19/2015 01:07:40 PM CDT

APPENDIX C

SUBJECT MATTER EXPERT INTERVIEW

Subject Matter Expert Questions and Discussion

Lyndsey Fyffe Dissertation Objective- SME Interviews

6/13/15

First, let me just thank you for letting us take up some of your time today to have this conversation. We are hoping that this work that we've done will help improve operations at your facility, so your input is so valuable in the process.

I'll start out by telling you a little bit about what we've done as a part of this research and then I'd love to have a conversation about a few areas we feel would make the most impact in terms of improving safety and efficiency of operations.

This research consisted of several phases of analysis of accident reports, including accidents investigated by the U.S. Chemical Safety Board, DOE Occurrence Reports for a few selected nuclear chemical operations and NRC occurrences from nuclear chemical facilities. For each report, we went through the process of analyzing its content. For the CSB reports, this involved looking at the staff-identified Key Issues, and then performing a content analysis of the text. We used a coding structure similar to OSHA's Process Safety Management Guidelines as they transition well into the chemical and nuclear fields. We repeated this coding process for the NRC and DOE occurrences and then grouped the occurrences into common issues that we could focus in on to make improvements.

What you will see during this conversation, is that for these key areas, we have a few of the most common issues highlighted. This is followed by a discussion of some metrics we think might be measurable and usable as indicators of an unsafe environment. As we go through, we are interested to know what your experience has been with the issue and what metrics, if any, you are already collecting or could collect. We would also like to gauge your opinion on using some of these in your operation.

1. From your operating experience, what are some of the more common issues that you face during operation, in particular, what are the most common causes of occurrences?
2. Engineering Controls:
    a. We have observed that design and engineering issues tend to be related to a lack of design features or safety controls, a lack of participation from engineers and design experts, and failure or underdesign of safety systems such as pressure relief devices or alarm systems. We have theorized that measuring and monitoring some of the following metrics would improve safety and efficiency in this area– do you agree, is it impactful?
        i. Amount of time since previous reviews of process or design
        ii. Number of processes or designs reviewed in a year
        iii. Number of engineers involved in process review or design
        iv. Number of controls for each possible event
        v. Number of identified hazards and controls reviewed in a given time (relatable to PHA)
        vi. Amount of time in between inspections and tests (mechanical integrity related)
        vii. Planned maintenance that occurs vs unplanned (maintenance related)
3. Operating Procedures
    a. We have observed that operating procedure related issues tend to be related to operators failing to follow the written procedure, outdated ineffective procedures, a lack of safety information in the procedure, and a lack of procedural information for abnormal circumstances (such as a higher than anticipated temperature or pressure reading). We have theorized that measuring and monitoring some of the following metrics would improve safety and efficiency in this area– do you agree, is it impactful?
        i. Number of procedures reviewed or updated in a given year

        ii. Number of operators or maintenance techs involved in procedure review (by survey?)
        iii. Number of procedures reviewed for content in a year
        iv. Number of operators or maintenance techs who believe procedures are current, accurate, and effective (by survey?)

4. Maintenance
    a. We have observed maintenance issues tend to be related to a lack of maintenance planning, or less than adequate performance of maintenance jobs. We have theorized that measuring and monitoring some of the following metrics would improve safety and efficiency in this area– do you agree, is it impactful?
        i. Number of safety critical plant items that have undergone maintenance vs. number of planned maintenance items
        ii. % of planned maintenance accomplished
        iii. Number of deferred maintenance requests or past due maintenance requests
        iv. Amount of time between maintenance requests and completion of maintenance work
5. Mechanical Integrity
    a. We have observed mechanical integrity issues that are particularly insightful in the discussions of aging infrastructure and facility degradation. Some of the highest contributors to mechanical integrity issues in the accidents we analyzed were degradation of materials and inoperable equipment, with an additional issue of these issues not being corrected in a timely manner. On top of these, we also found issues with a lack of inspections and tests to ensure integrity of systems. We have theorized that measuring and monitoring some of the following metrics would improve safety and efficiency in this area– do you agree, is it impactful?
        i. Number of inspections completed during a time period vs. number of inspections due during that time period
        ii. Amount of time between issuing corrective action and completing the corrective action (deficiencies corrected in a safe and timely manner)
        iii. Amount of time plant is in operation with any safety component in a failed state (broken down or failed inspection)
        iv. Percentage of plant start-ups with no safety problems documented or realized
6. Hazards Analysis
    a. The most common issue that we observed in the area of hazards analysis, is simply that no hazards analysis was performed. While this may be less of an issue in the DOE environment, other observations included inadequacies in the HA, such as the acceptance of lower tier safety controls for certain scenarios and a lack of necessary expertise in the team performing the assessment. We also observed

that many facilities involved in accidents did not have a system in place to update these assessments and track the implementation of findings from them. We have theorized that measuring and monitoring some of the following metrics would improve safety and efficiency in this area– do you agree, is it impactful?

   i. Number of identified hazards and controls reviewed in a given time (relatable to safety systems)
   ii. Amount of time since previous review of process hazards
   iii. Number of operators and maintenance techs who have been trained on the PHA
   iv. Pertinent subject matter experts involved in the PHA development
   v. Operations and maintenance personnel involved in the PHA development

7. Incident Investigation
   a. We observed incident investigation issues across many of the accidents in the chemical industry. In many cases, there was a less severe precursor accident in the time leading to the major accident that was not investigated or remediated. In many cases, the larger accident occurs before follow-up on action items for the precursor. We have theorized that measuring and monitoring some of the following metrics would improve safety and efficiency in this area– do you agree, is it impactful?
      i. Number of open action items vs. total number of action items from previous occurrences (ties to safety culture- organizational learning)
      ii. Number of lessons learned developed as a part of ORPS reports or other incident reporting
      iii. Frequency of updates to controls or procedures
      iv. Number of operators and maintenance techs who are familiar with operating history of facility and lessons learned from accidents (by survey?)
8. Emergency Planning
   a. Understanding that DOE sites have a different protocol for emergency response than a private chemical operation, we have observed that emergency planning and response issues tend to be centered around a lack of emergency planning, leaving employees unsure of what to do or who to contact, causing communication issues and confusion among responders, and a lack of training and resources for emergency responders, leaving them unsure of the hazards and not able to provide the most efficient assistance to the facility. We have theorized that measuring and monitoring some of the following metrics would improve safety and efficiency in this area– do you agree, is it impactful?
      i. Number of local (county? City?) Emergency Responders trained in facility (e.g. chemical or radiological) hazards and response?
      ii. Hours of training available to emergency responders vs. total hours taken

iii. Number of emergency drills performed in a time period vs. number scheduled
iv. Amount of time since last update of emergency plan
v. Number of personnel trained as point person responsible for facility emergency
vi. Number of workers who feel confident following emergency plan in emergency (survey?)

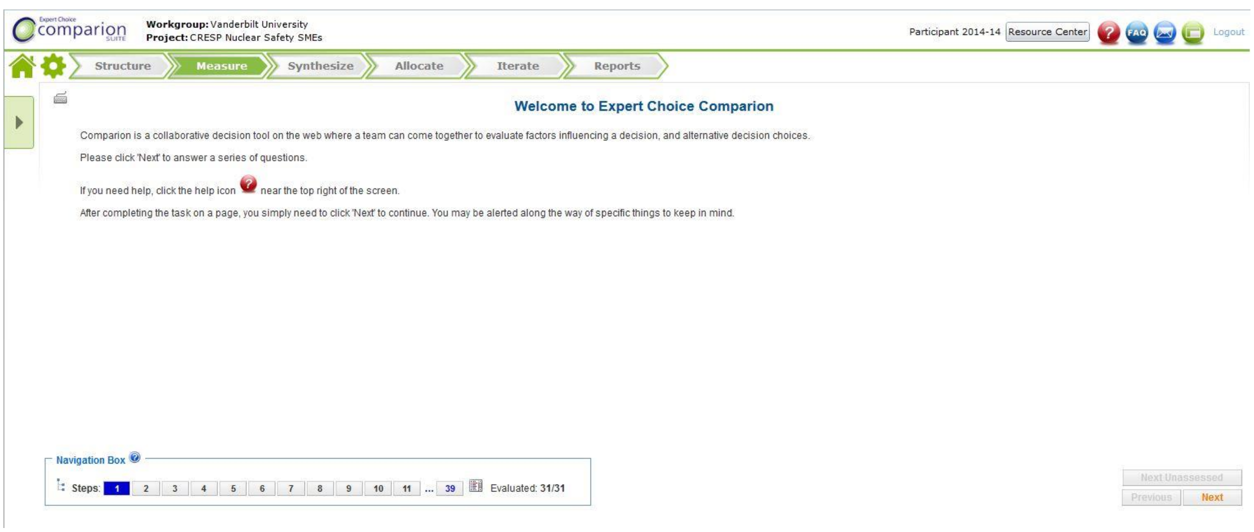
9. What metrics that we haven't discussed, if any, are you currently analyzing as leading performance indicators?
10. Are there any lagging indicators we should be knowledgeable about that might also provide some insight into this research?
11. Do you have any questions or concerns about the analysis we've done or the discussion we've had today?

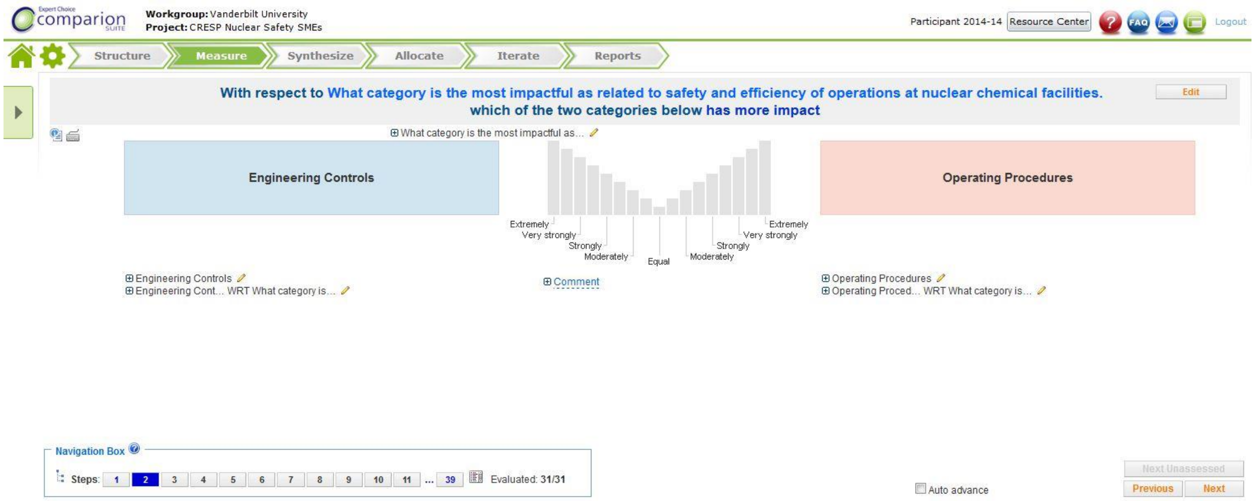
APPENDIX D

SUBJECT MATTER EXPERT SURVEY TOOL

Survey Tool Questions- Nuclear Safety Subject Matter Expert Elicitation for Improvement of Performance Measures

Note: This survey tool is web-based, and therefore is interactive with participants. The following screenshots represent the questions the subjects will answer and the screens they will view as they work through the survey. There are screens that provide a review of their responses at the end of each section (screens 12, 19, 23, 27, 34, 38).

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Project: CRESP Nuclear Safety SMEs
Participant 2014-14
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Reports
With respect to What category is the most impactful as related to safety and efficiency of operations at nuclear chemical facilities. which of the two categories below has more impact
Edit
What category is the most impactful as...
Engineering Controls
Operating Procedures
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Engineering Controls
Engineering Cont... WRT What category is...
Comment
Operating Procedures
Operating Proced... WRT What category is...
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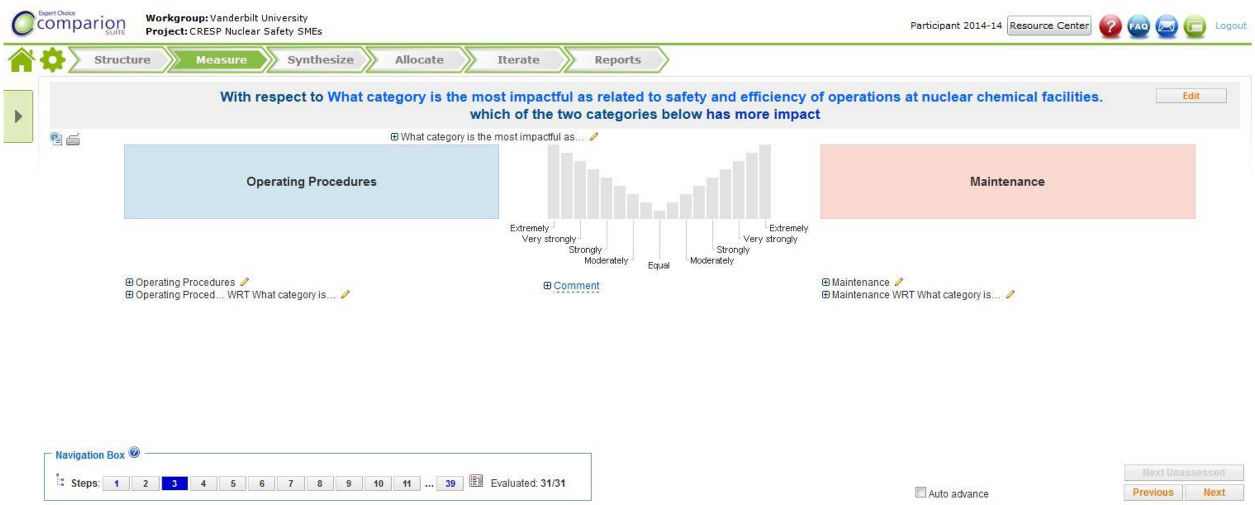
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Reports
With respect to What category is the most impactful as related to safety and efficiency of operations at nuclear chemical facilities. which of the two categories below has more impact
Edit
What category is the most impactful as...
Operating Procedures
Maintenance
Extremely
Very strongly
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Operating Procedures
Operating Proced... WRT What category is...
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Maintenance WRT What category is...
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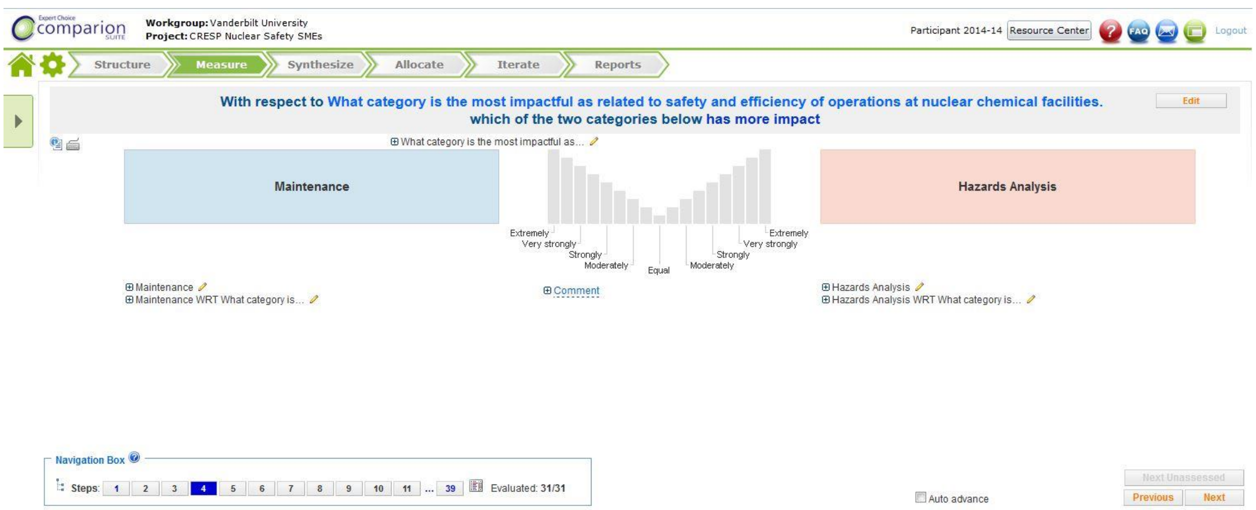
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Project: CRESP Nuclear Safety SMEs
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With respect to What category is the most impactful as related to safety and efficiency of operations at nuclear chemical facilities. which of the two categories below has more impact
Edit
What category is the most impactful as...
Maintenance
Hazards Analysis
Extremely
Very strongly
Strongly
Moderately
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Strongly
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Extremely
Maintenance
Maintenance WRT What category is...
Comment
Hazards Analysis
Hazards Analysis WRT What category is...
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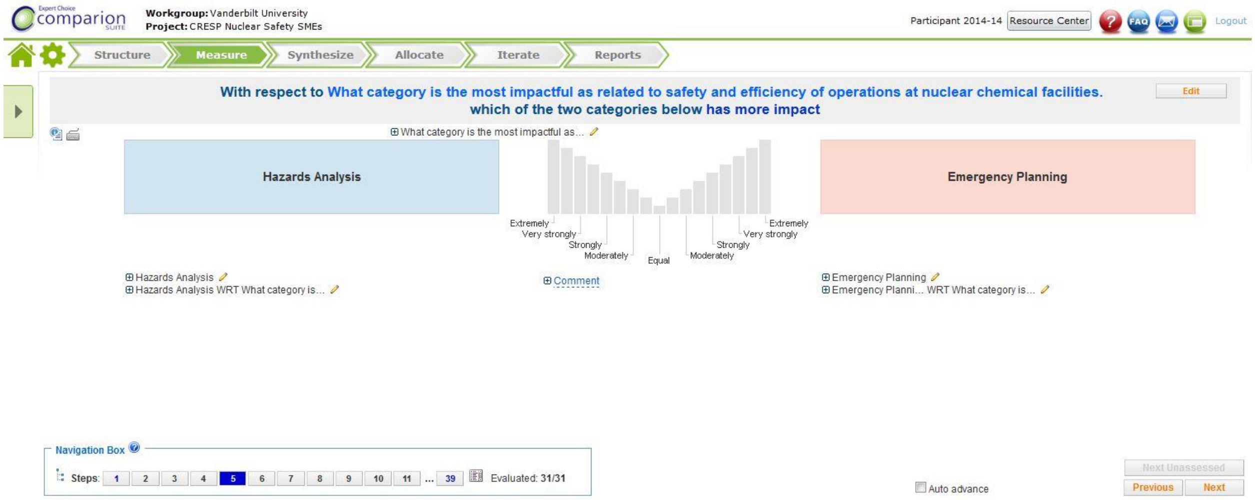
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Emergency Planning
Extremely
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Hazards Analysis
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Comment
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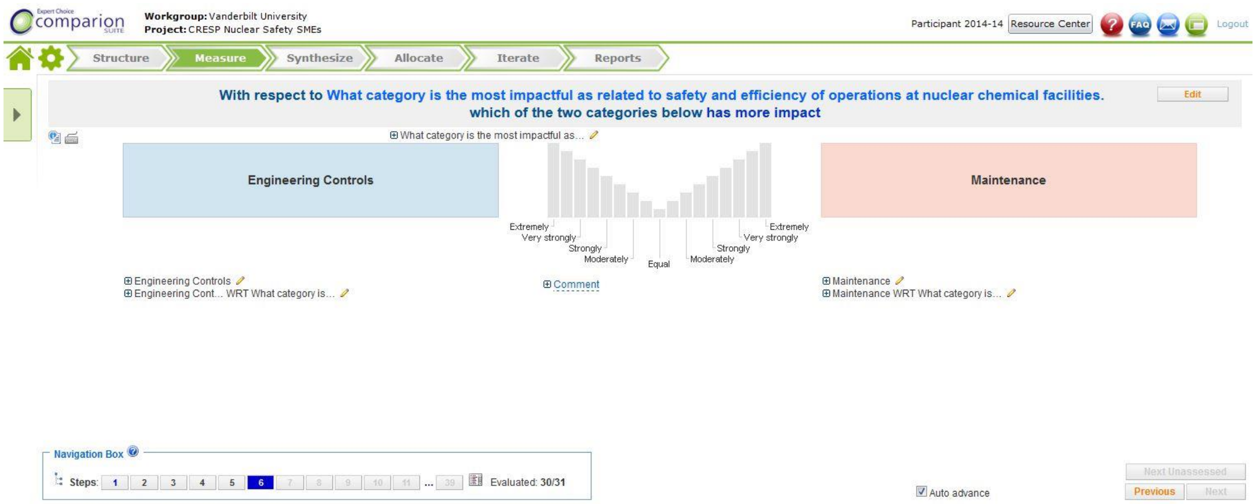
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Edit
What category is the most impactful as...
Engineering Controls
Maintenance
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Engineering Controls
Engineering Cont... WRT What category is...
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Maintenance WRT What category is...
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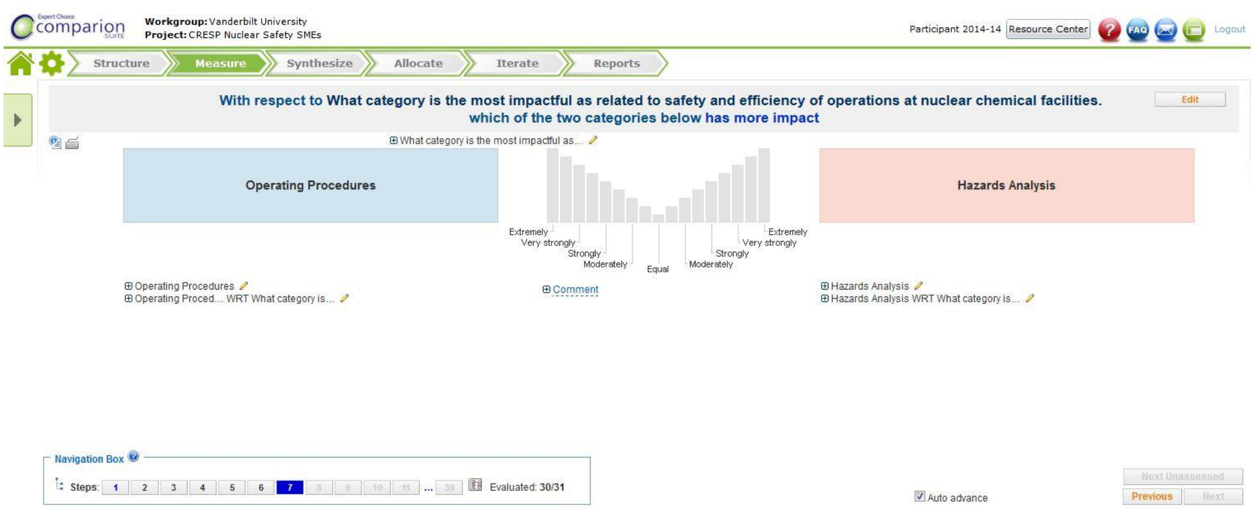
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Operating Procedures
Operating Proced... WRT What category is...
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Hazards Analysis
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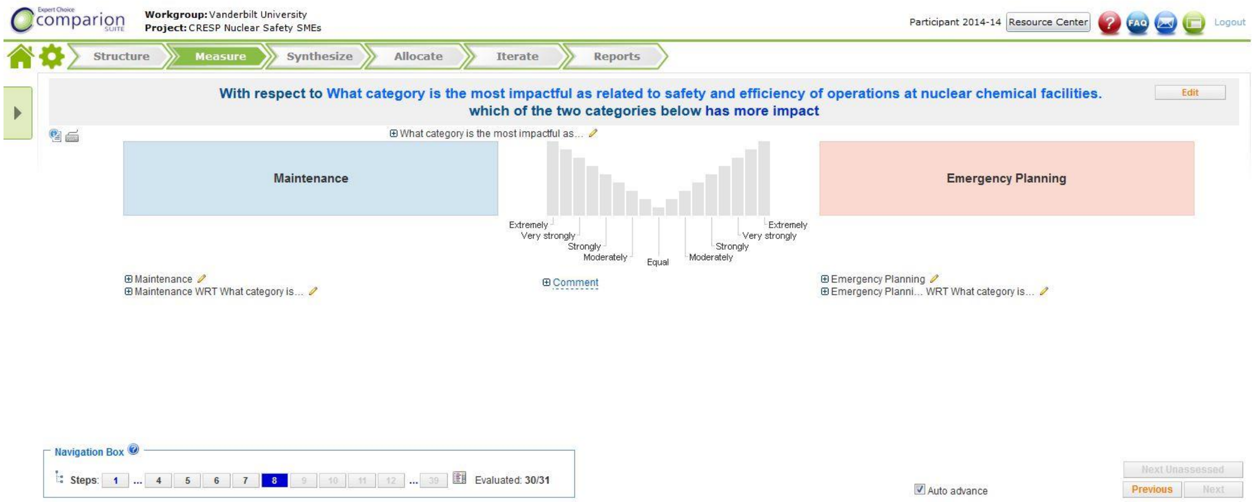
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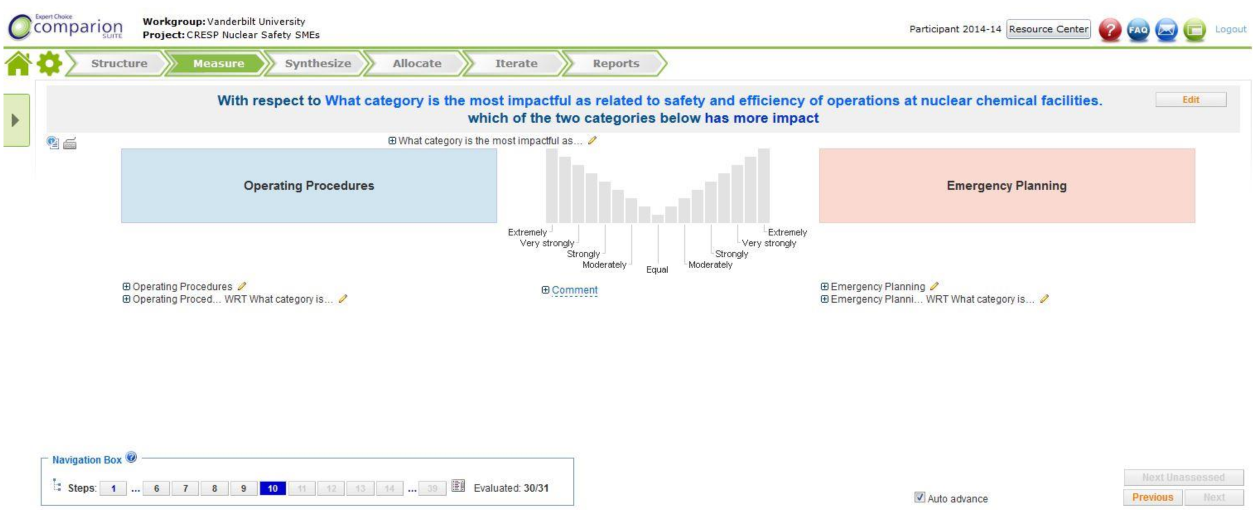
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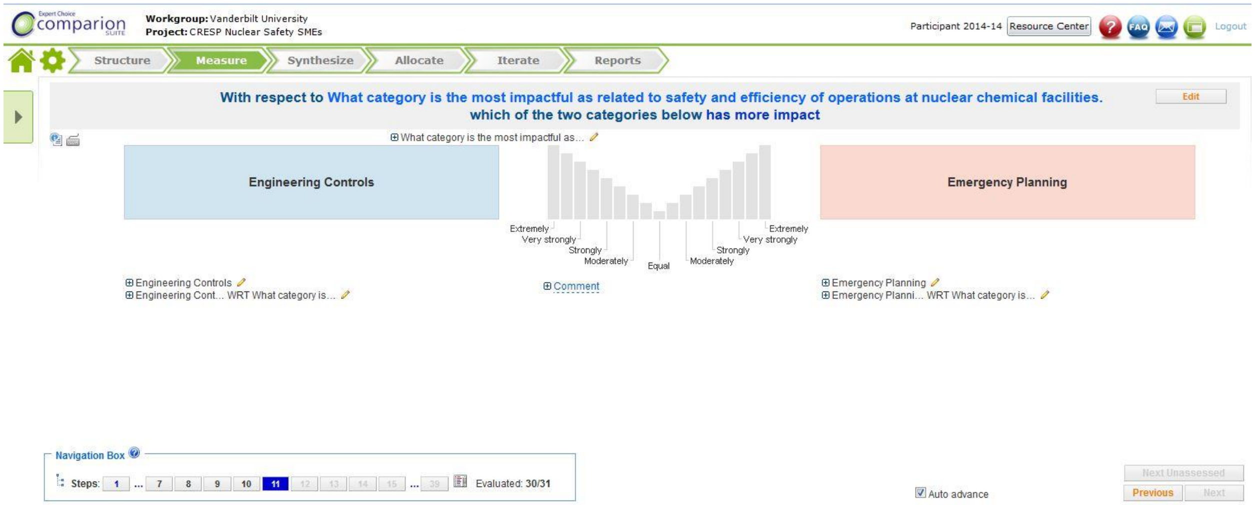
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Comment
Emergency Planning
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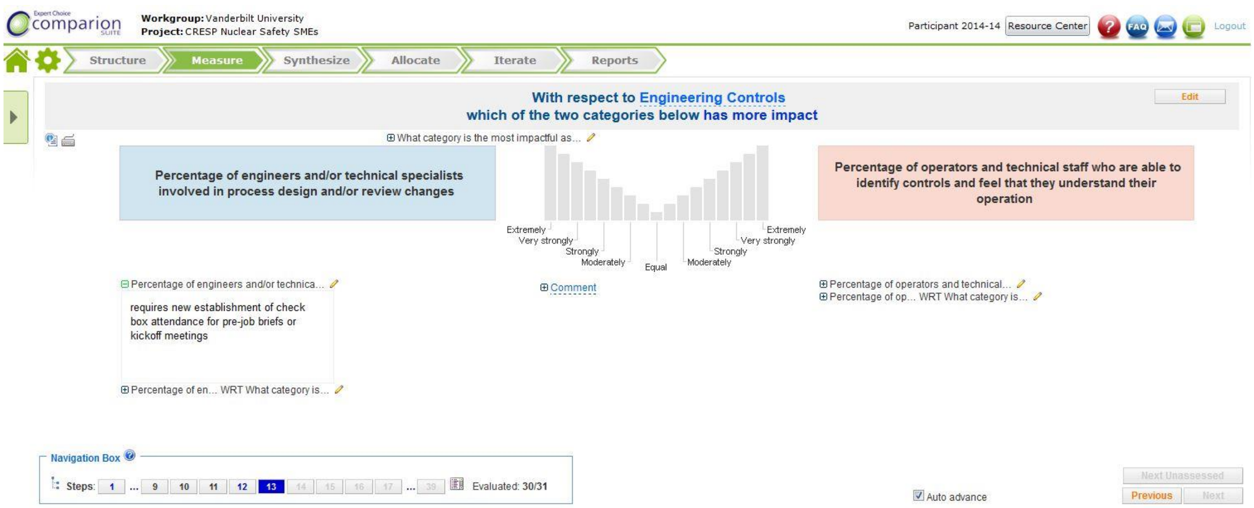
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With respect to Engineering Controls
which of the two categories below has more impact
Edit
What category is the most impactful as...
Percentage of engineers and/or technical specialists involved in process design and/or review changes
Percentage of operators and technical staff who are able to identify controls and feel that they understand their operation
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Percentage of engineers and/or technica...
requires new establishment of check box attendance for pre-job briefs or kickoff meetings
Percentage of en... WRT What category is...
Comment
Percentage of operators and technical...
Percentage of op... WRT What category is...
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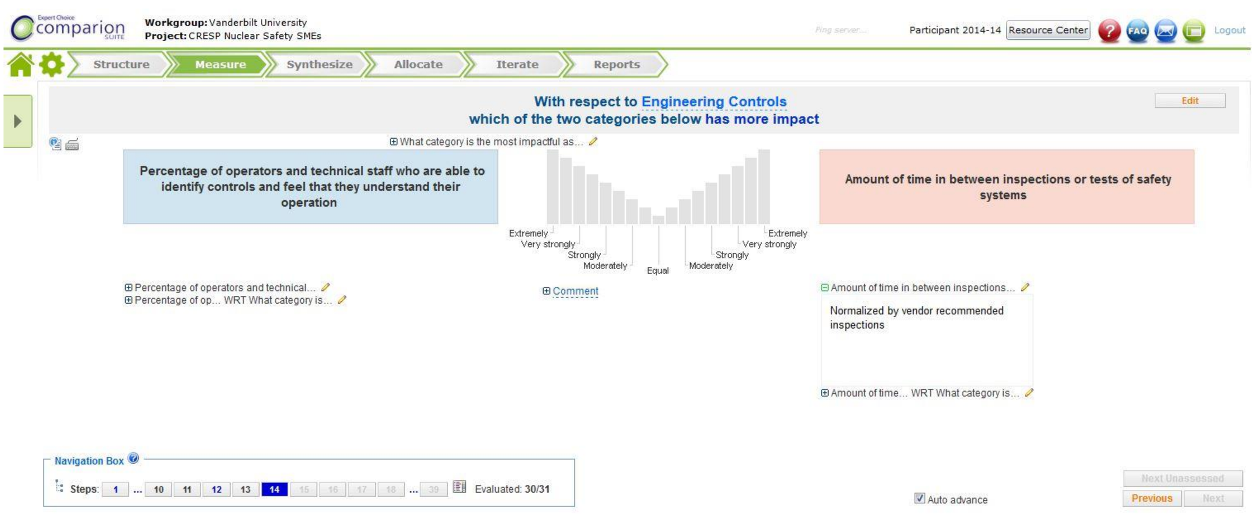
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With respect to Engineering Controls
which of the two categories below has more impact
Edit
What category is the most impactful as...
Percentage of operators and technical staff who are able to identify controls and feel that they understand their operation
Amount of time in between inspections or tests of safety systems
Extremely
Very strongly
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Percentage of operators and technical...
Percentage of op... WRT What category is...
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Normalized by vendor recommended inspections
Amount of time... WRT What category is...
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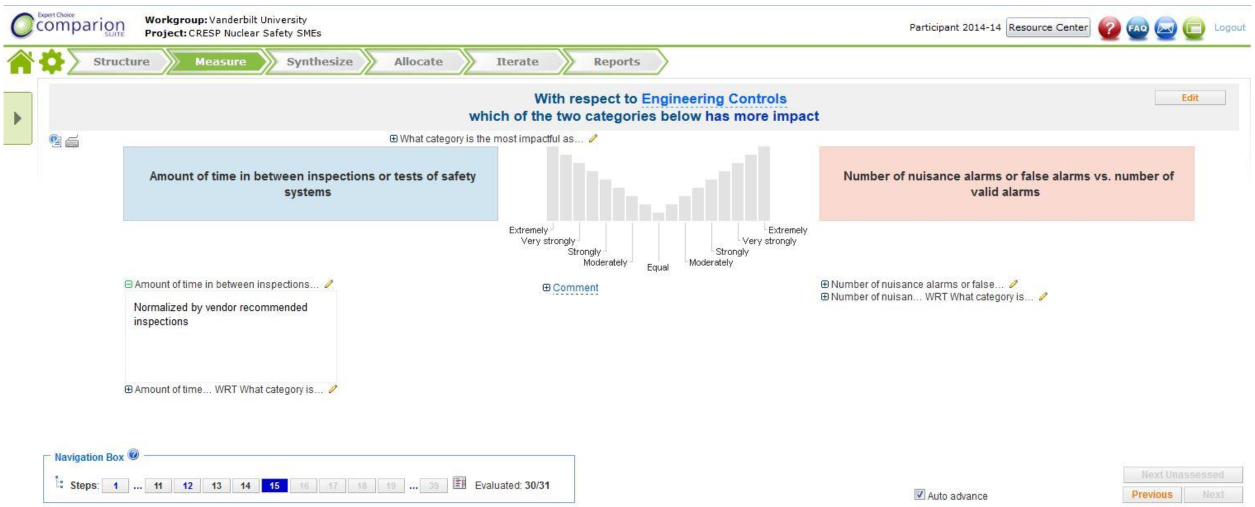
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Edit
With respect to Engineering Controls
which of the two categories below has more impact
What category is the most impactful as...
Amount of time in between inspections or tests of safety systems
Number of nuisance alarms or false alarms vs. number of valid alarms
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Amount of time in between inspections...
Normalized by vendor recommended inspections
Amount of time... WRT What category is...
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Number of nuisance alarms or false...
Number of nuisan... WRT What category is...
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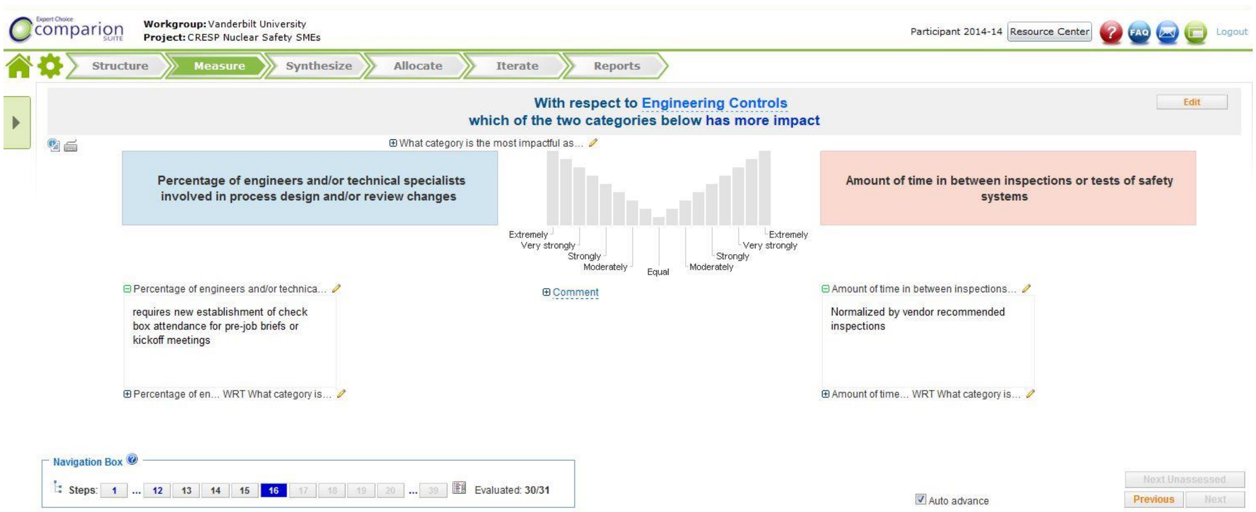
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Percentage of engineers and/or technica...
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Percentage of en... WRT What category is...
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Amount of time... WRT What category is...
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Number of nuisance alarms or false alarms vs. number of valid alarms
Extremely
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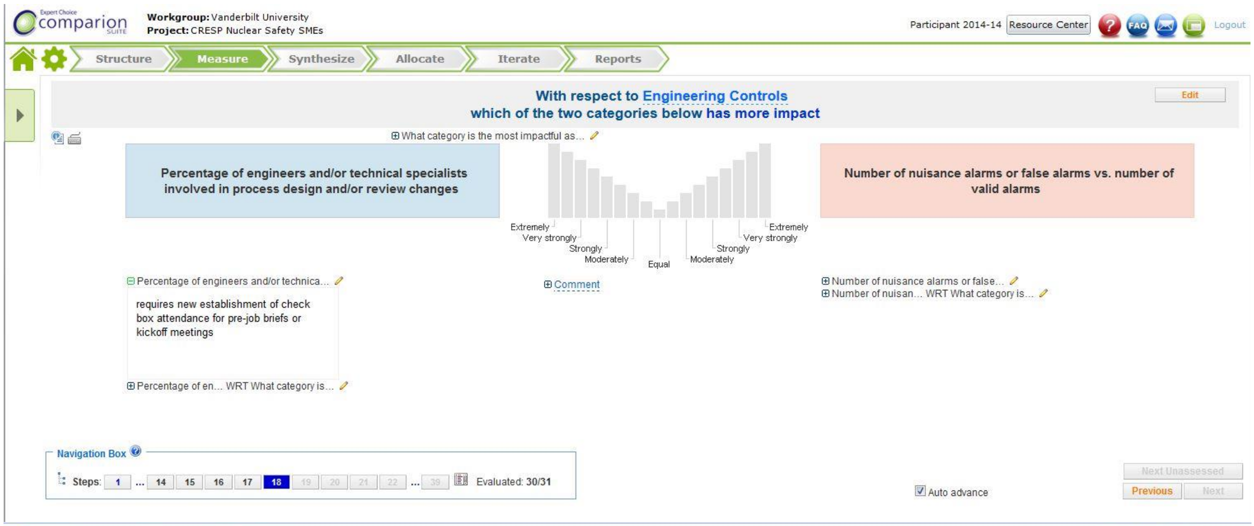
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Number of nuisance alarms or false...
Number of nuisan... WRT What category is...
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Participant 2014-14
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Allocate
Iterate
Reports
With respect to Operating Procedures
which of the two categories below has more impact
Edit
What category is the most impactful as...
Percentage of procedures reviewed for content in a year
Number of operators or maintenance technicians whose experience is that procedures are current, accurate, and effective (by survey)
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Percentage of procedures reviewed for...
Percentage of pr... WRT What category is...
Comment
Number of operators or maintenance...
Number of operat... WRT What category is...
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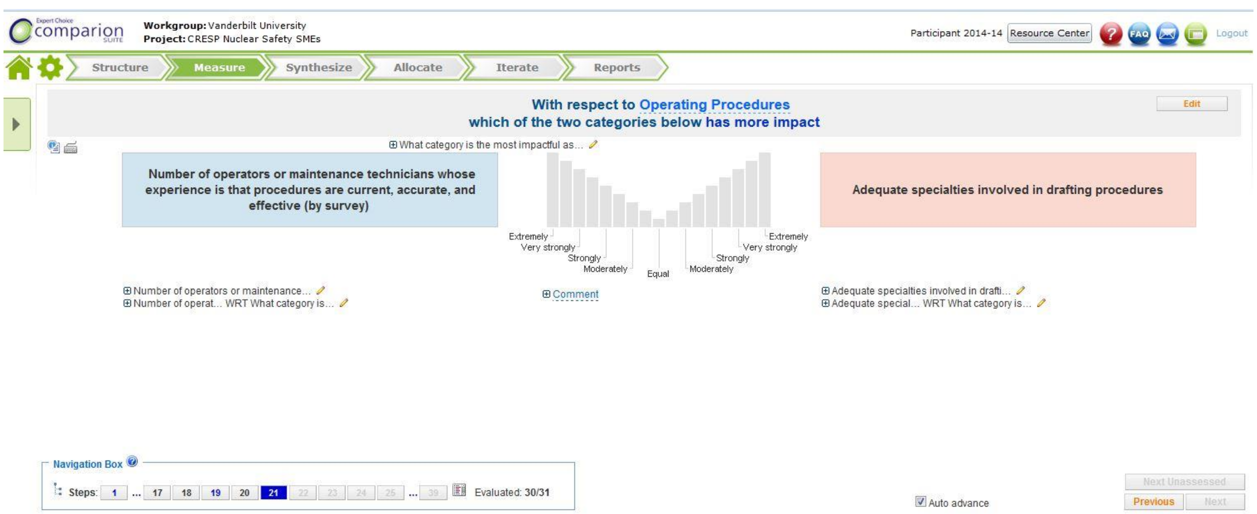
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Participant 2014-14
Resource Center
Logout
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Allocate
Iterate
Reports
With respect to Operating Procedures
which of the two categories below has more impact
Edit
What category is the most impactful as...
Number of operators or maintenance technicians whose experience is that procedures are current, accurate, and effective (by survey)
Adequate specialties involved in drafting procedures
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
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Extremely
Number of operators or maintenance...
Number of operat... WRT What category is...
Comment
Adequate specialties involved in drafti...
Adequate special... WRT What category is...
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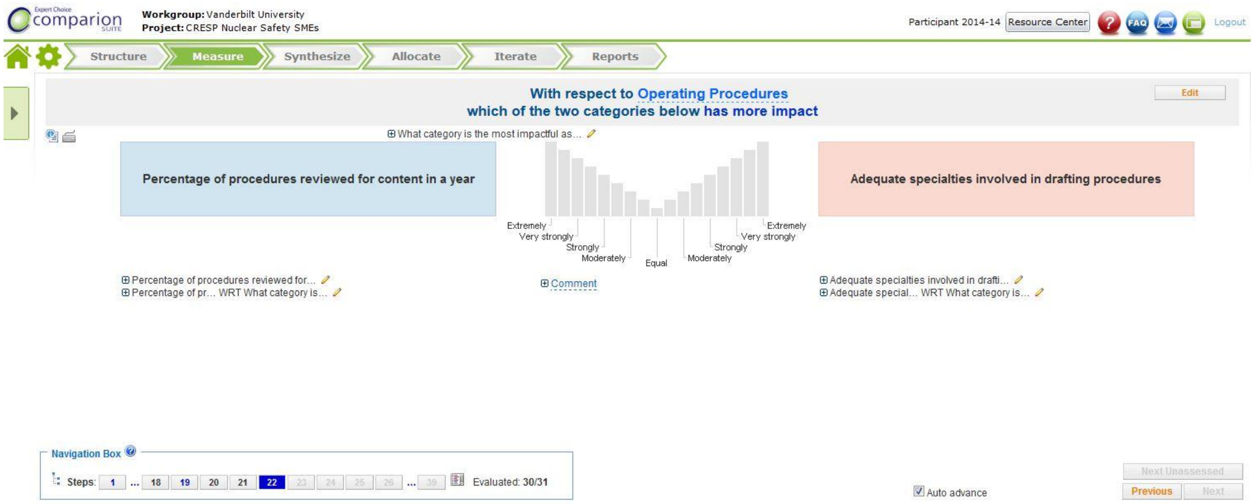
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Percentage of procedures reviewed for…
Percentage of pr… WRT What category is…
Comment
Adequate specialties involved in drafti…
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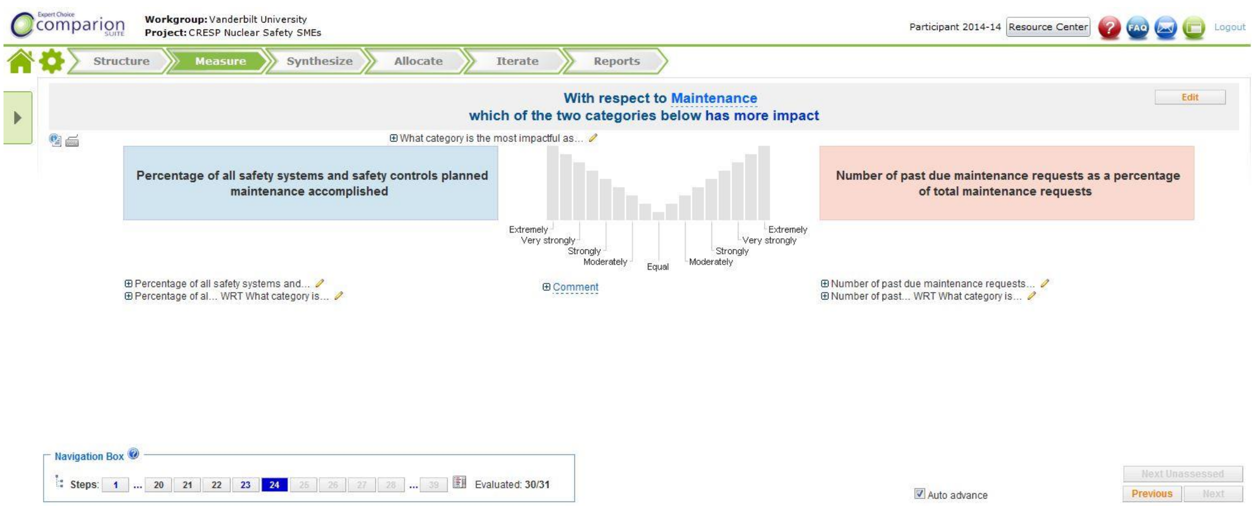
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Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14
Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
With respect to Maintenance
which of the two categories below has more impact
Edit
What category is the most impactful as…
Percentage of all safety systems and safety controls planned maintenance accomplished
Number of past due maintenance requests as a percentage of total maintenance requests
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Percentage of all safety systems and…
Percentage of al… WRT What category is…
Comment
Number of past due maintenance requests…
Number of past… WRT What category is…
Navigation Box
Steps: 1 … 20 21 22 23 24 25 26 27 28 … 39
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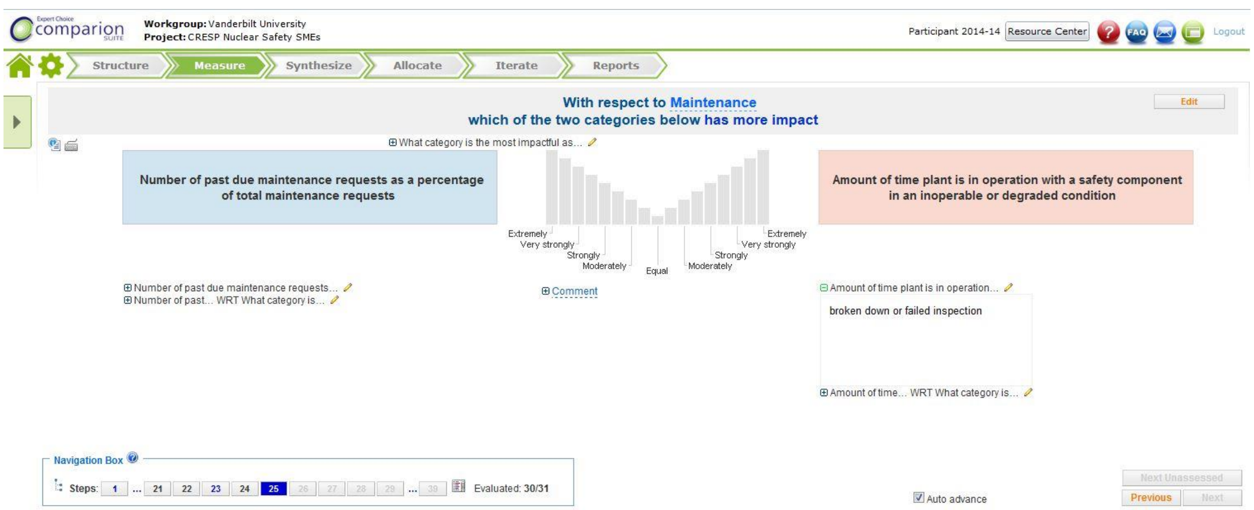
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Synthesize
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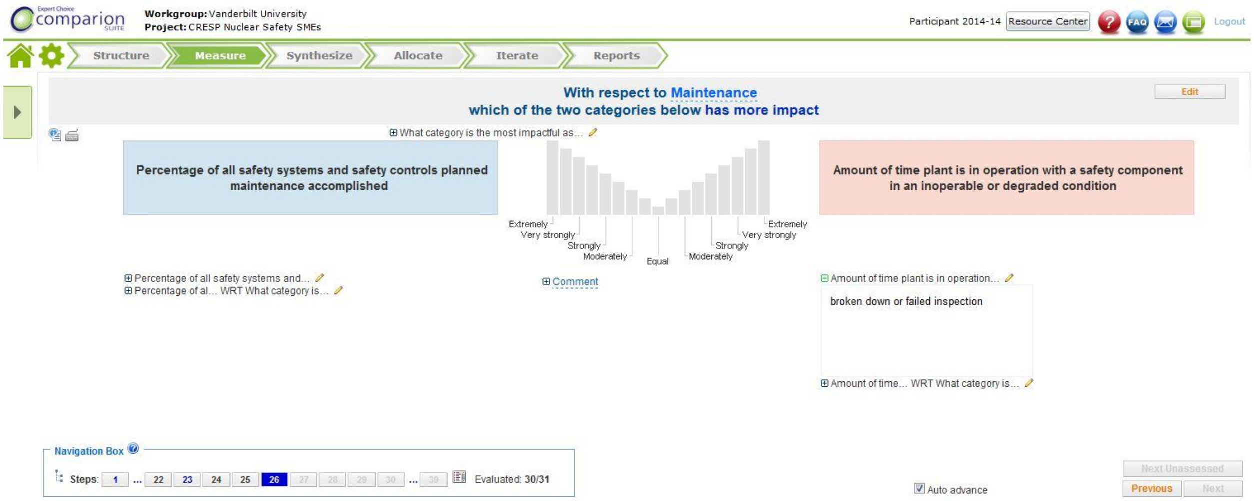
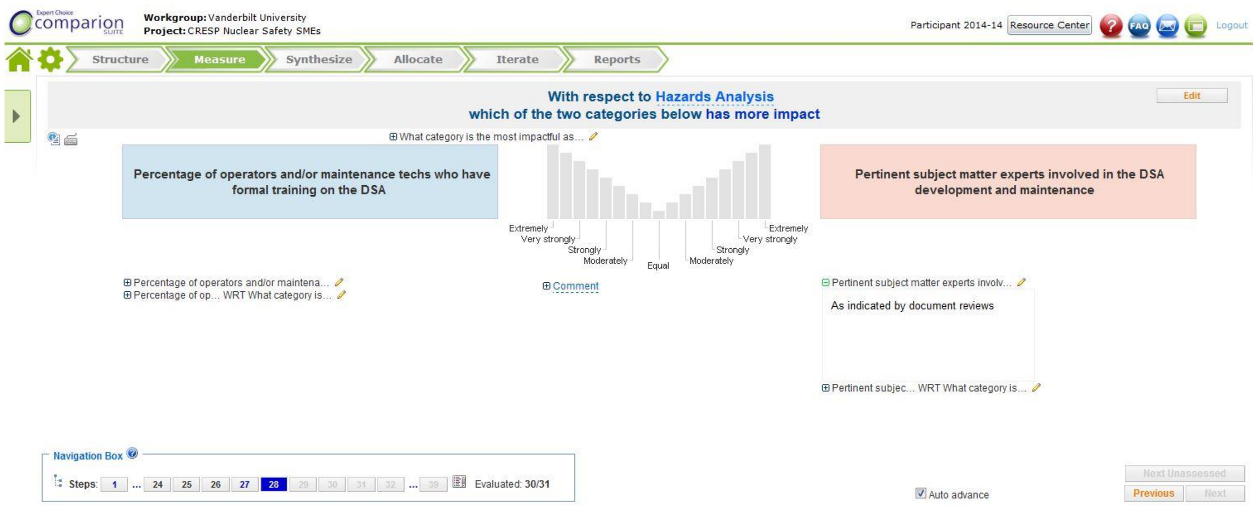
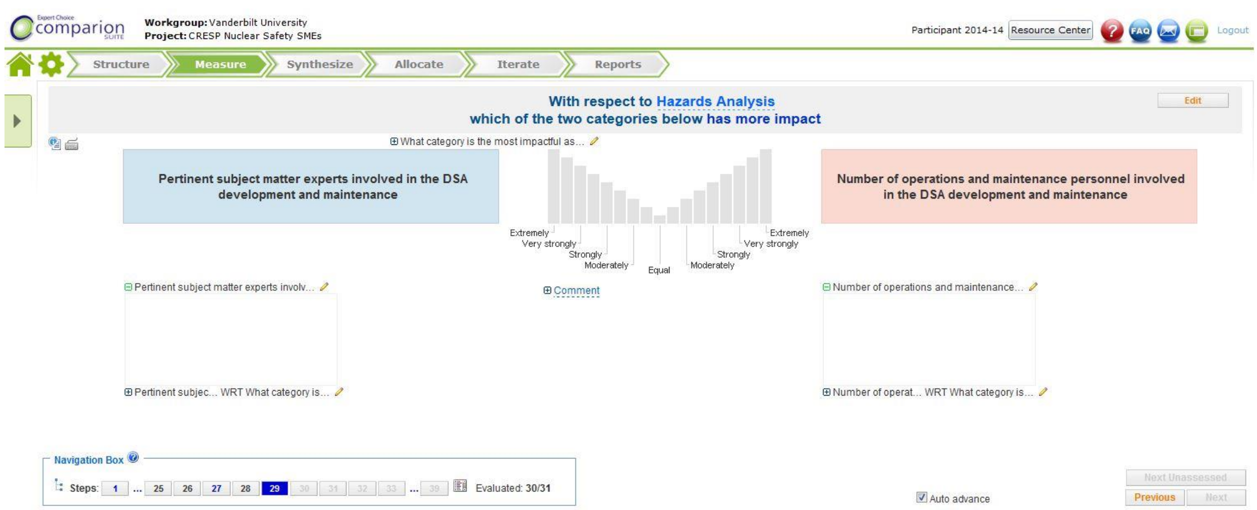
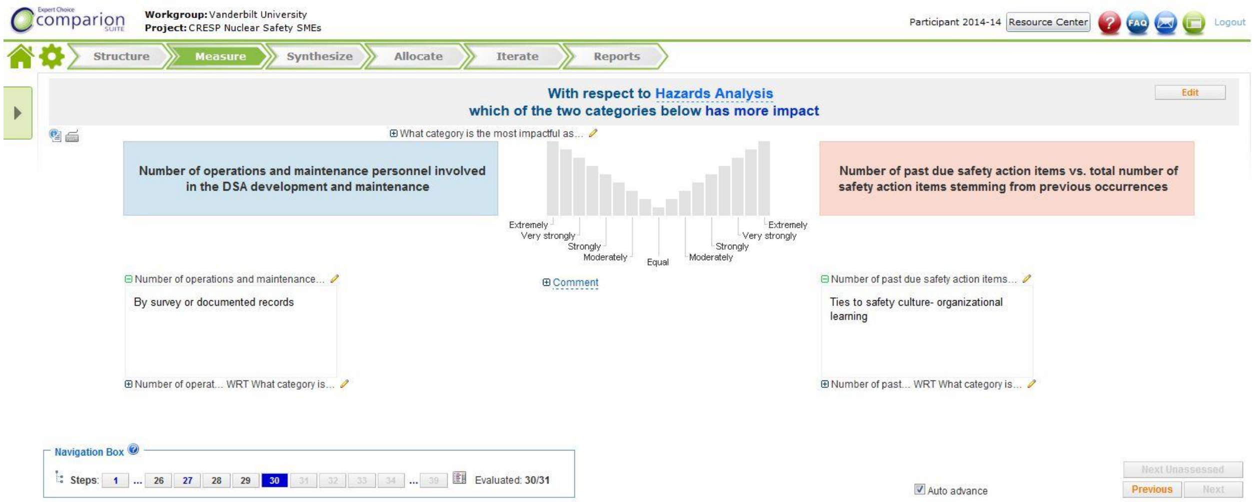
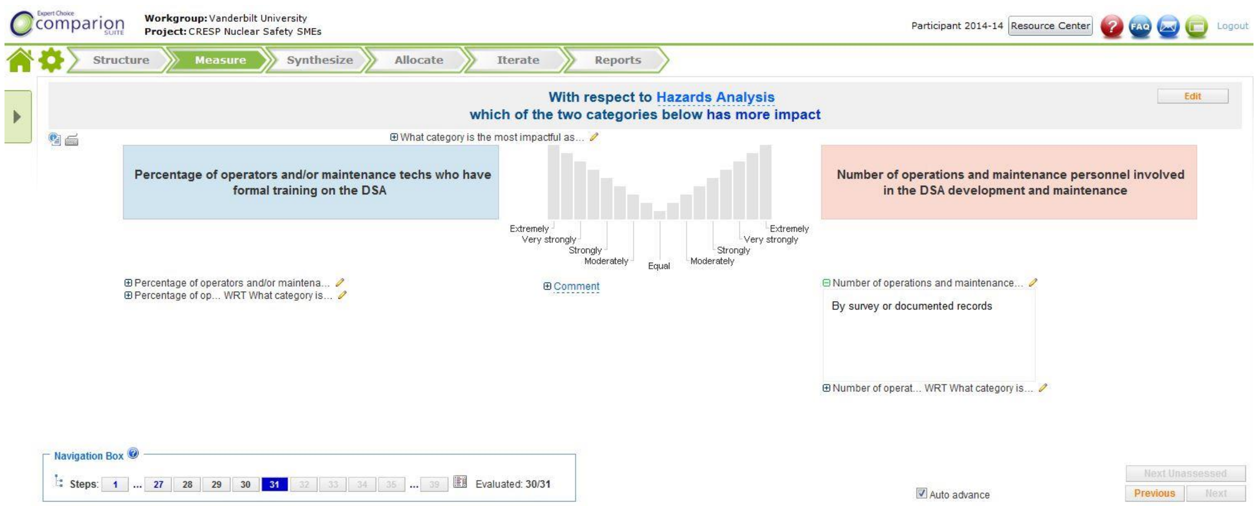
Reports
With respect to Maintenance
which of the two categories below has more impact
Edit
What category is the most impactful as…
Number of past due maintenance requests as a percentage of total maintenance requests
Amount of time plant is in operation with a safety component in an inoperable or degraded condition
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Number of past due maintenance requests…
Number of past… WRT What category is…
Comment
Amount of time plant is in operation…
broken down or failed inspection
Amount of time… WRT What category is…
Navigation Box
Steps: 1 … 21 22 23 24 25 26 27 28 29 … 39
Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next

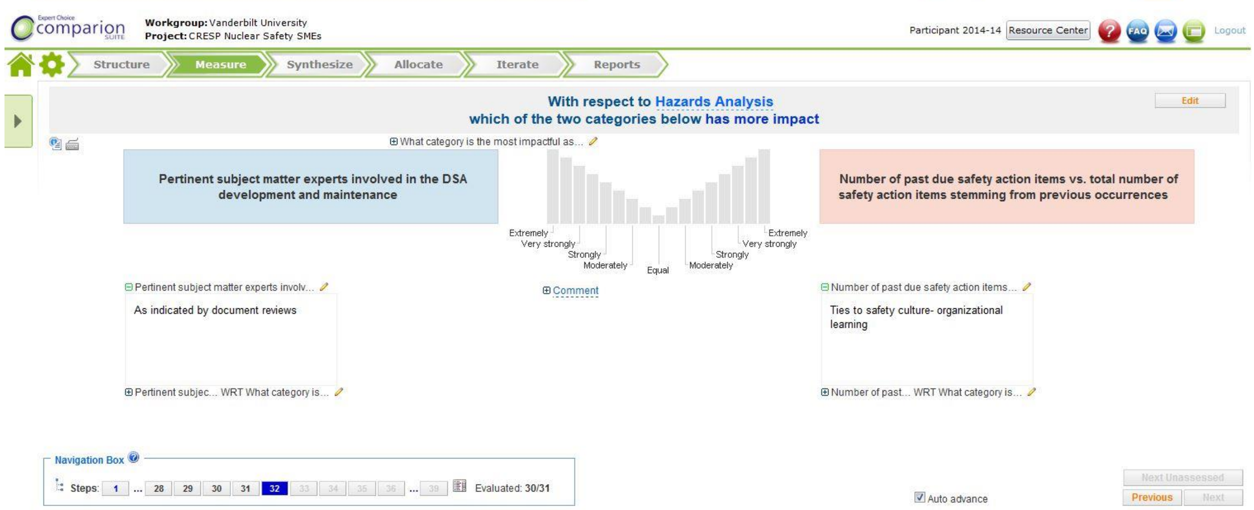

comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14 Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
With respect to Maintenance
which of the two categories below has more impact
Edit
What category is the most impactful as...
Percentage of all safety systems and safety controls planned maintenance accomplished
Amount of time plant is in operation with a safety component in an inoperable or degraded condition
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Percentage of all safety systems and...
Percentage of al... WRT What category is...
Comment
Amount of time plant is in operation...
broken down or failed inspection
Amount of time... WRT What category is...
Navigation Box
Steps: 1 ... 22 23 24 25 26 27 28 29 30 ... 39 Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next

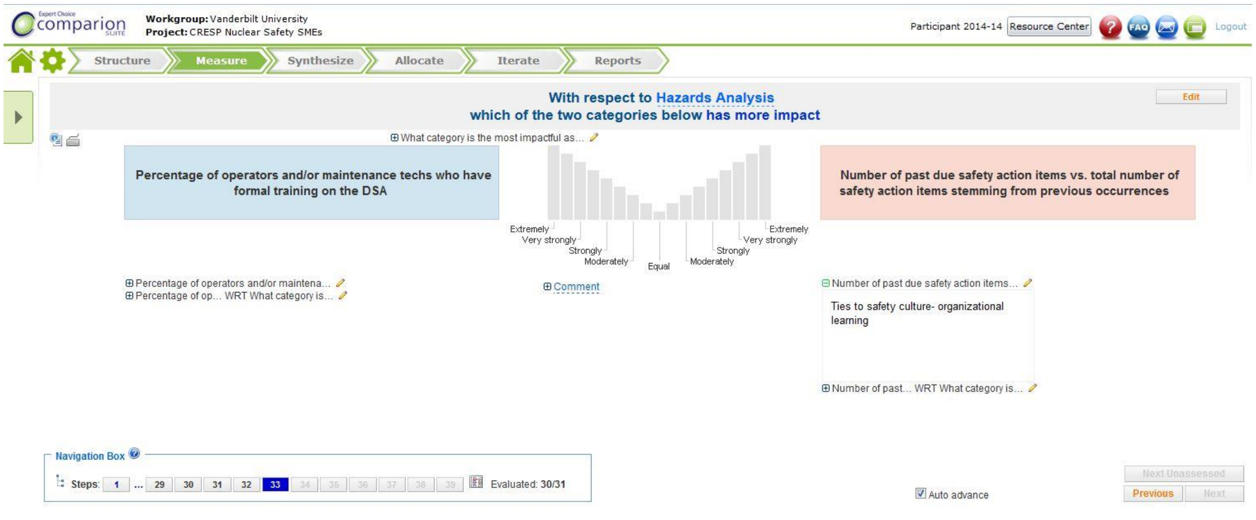
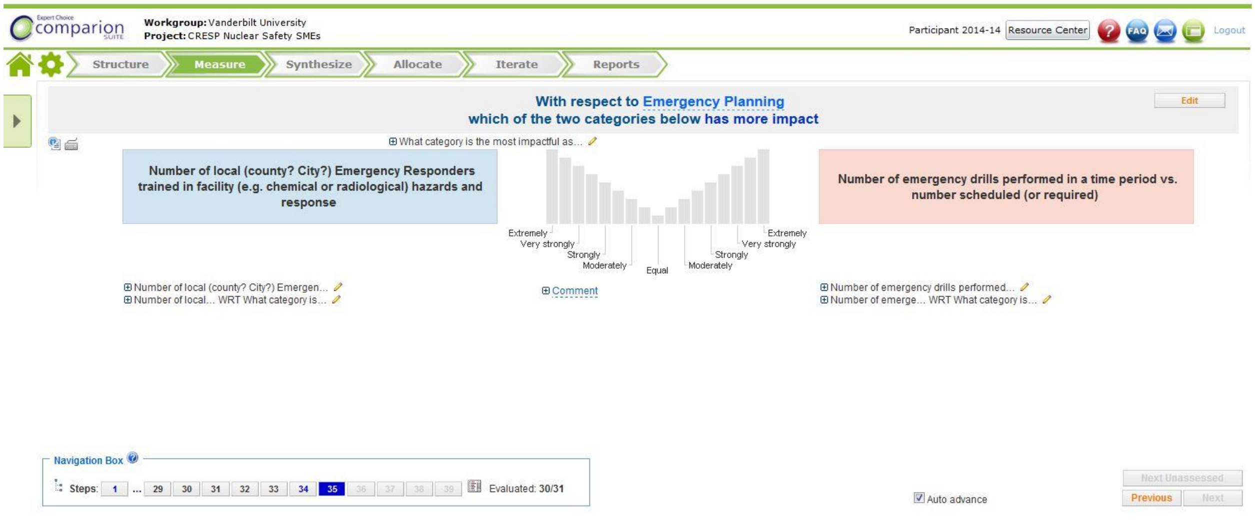

comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14 Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
With respect to Hazards Analysis
which of the two categories below has more impact
Edit
What category is the most impactful as...
Percentage of operators and/or maintenance techs who have formal training on the DSA
Pertinent subject matter experts involved in the DSA development and maintenance
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Percentage of operators and/or maintena...
Percentage of op... WRT What category is...
Comment
Pertinent subject matter experts involv...
As indicated by document reviews
Pertinent subjec... WRT What category is...
Navigation Box
Steps: 1 ... 24 25 26 27 28 29 30 31 32 ... 39 Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next

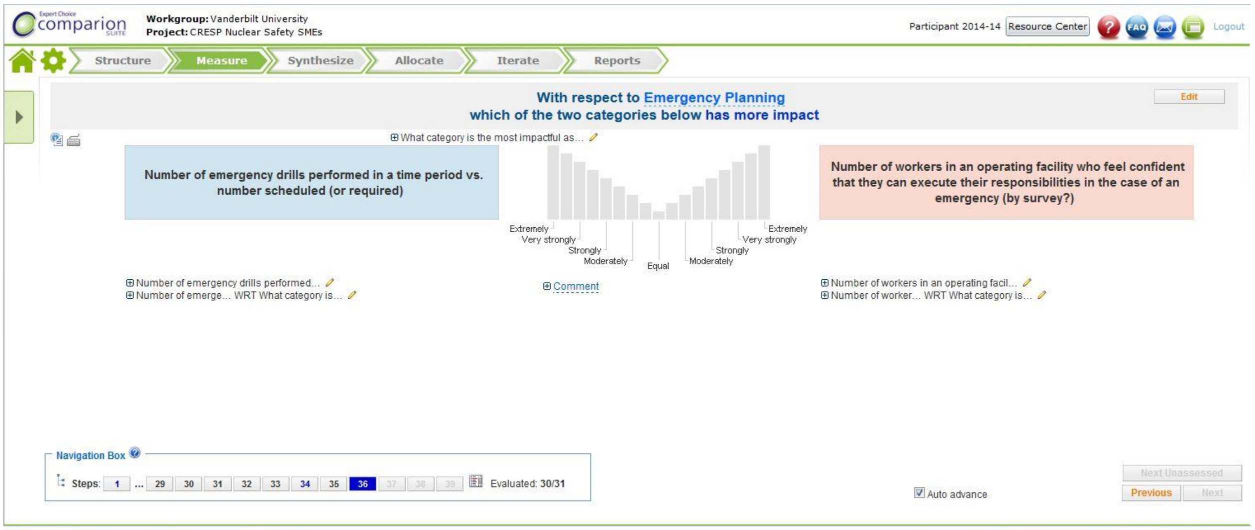

comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14 Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
With respect to Hazards Analysis
which of the two categories below has more impact
Edit
What category is the most impactful as...
Pertinent subject matter experts involved in the DSA development and maintenance
Number of operations and maintenance personnel involved in the DSA development and maintenance
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Pertinent subject matter experts involv...
Pertinent subjec... WRT What category is...
Comment
Number of operations and maintenance...
Number of operat... WRT What category is...
Navigation Box
Steps: 1 ... 25 26 27 28 29 30 31 32 33 ... 39 Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next


comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14
Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
Edit
With respect to Hazards Analysis
which of the two categories below has more impact
What category is the most impactful as...
Number of operations and maintenance personnel involved in the DSA development and maintenance
Number of past due safety action items vs. total number of safety action items stemming from previous occurrences
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Number of operations and maintenance...
By survey or documented records
Comment
Number of past due safety action items...
Ties to safety culture- organizational learning
Number of operat... WRT What category is...
Number of past... WRT What category is...
Navigation Box
Steps: 1 ... 26 27 28 29 30 31 32 33 34 ... 39
Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next


comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14
Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
Edit
With respect to Hazards Analysis
which of the two categories below has more impact
What category is the most impactful as...
Percentage of operators and/or maintenance techs who have formal training on the DSA
Number of operations and maintenance personnel involved in the DSA development and maintenance
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Percentage of operators and/or maintena...
Percentage of op... WRT What category is...
Comment
Number of operations and maintenance...
By survey or documented records
Number of operat... WRT What category is...
Navigation Box
Steps: 1 ... 27 28 29 30 31 32 33 34 35 ... 39
Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next


comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14
Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
Edit
With respect to Hazards Analysis
which of the two categories below has more impact
What category is the most impactful as...
Pertinent subject matter experts involved in the DSA development and maintenance
Number of past due safety action items vs. total number of safety action items stemming from previous occurrences
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Pertinent subject matter experts involv...
As indicated by document reviews
Comment
Number of past due safety action items...
Ties to safety culture- organizational learning
Pertinent subjec... WRT What category is...
Number of past... WRT What category is...
Navigation Box
Steps: 1 ... 28 29 30 31 32 33 34 35 36 ... 39
Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next


comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14 Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
Edit
With respect to Hazards Analysis
which of the two categories below has more impact
What category is the most impactful as...
Percentage of operators and/or maintenance techs who have formal training on the DSA
Number of past due safety action items vs. total number of safety action items stemming from previous occurrences
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Percentage of operators and/or maintena...
Percentage of op... WRT What category is...
Comment
Number of past due safety action items...
Ties to safety culture- organizational learning
Number of past... WRT What category is...
Navigation Box
Steps: 1 ... 29 30 31 32 33 34 35 36 37 38 39
Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next

comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14 Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
Edit
With respect to Emergency Planning
which of the two categories below has more impact
What category is the most impactful as...
Number of local (county? City?) Emergency Responders trained in facility (e.g. chemical or radiological) hazards and response
Number of emergency drills performed in a time period vs. number scheduled (or required)
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Number of local (county? City?) Emergen...
Number of local... WRT What category is...
Comment
Number of emergency drills performed...
Number of emerge... WRT What category is...
Navigation Box
Steps: 1 ... 29 30 31 32 33 34 35 36 37 38 39
Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next


comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14
Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
With respect to Emergency Planning
which of the two categories below has more impact
Edit
What category is the most impactful as...
Number of emergency drills performed in a time period vs. number scheduled (or required)
Number of workers in an operating facility who feel confident that they can execute their responsibilities in the case of an emergency (by survey?)
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Number of emergency drills performed...
Number of emerge... WRT What category is...
Comment
Number of workers in an operating facil...
Number of worker... WRT What category is...
Navigation Box
Steps: 1 ... 29 30 31 32 33 34 35 36 37 38 39
Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next


comparion
Workgroup: Vanderbilt University
Project: CRESP Nuclear Safety SMEs
Participant 2014-14
Resource Center
Logout
Structure
Measure
Synthesize
Allocate
Iterate
Reports
With respect to Emergency Planning
which of the two categories below has more impact
Edit
What category is the most impactful as...
Number of local (county? City?) Emergency Responders trained in facility (e.g. chemical or radiological) hazards and response
Number of workers in an operating facility who feel confident that they can execute their responsibilities in the case of an emergency (by survey?)
Extremely
Very strongly
Strongly
Moderately
Equal
Moderately
Strongly
Very strongly
Extremely
Number of local (county? City?) Emergen...
Number of local... WRT What category is...
Comment
Number of workers in an operating facil...
Number of worker... WRT What category is...
Navigation Box
Steps: 1 ... 29 30 31 32 33 34 35 36 37 38 39
Evaluated: 30/31
Auto advance
Next Unassessed
Previous
Next

APPENDIX E

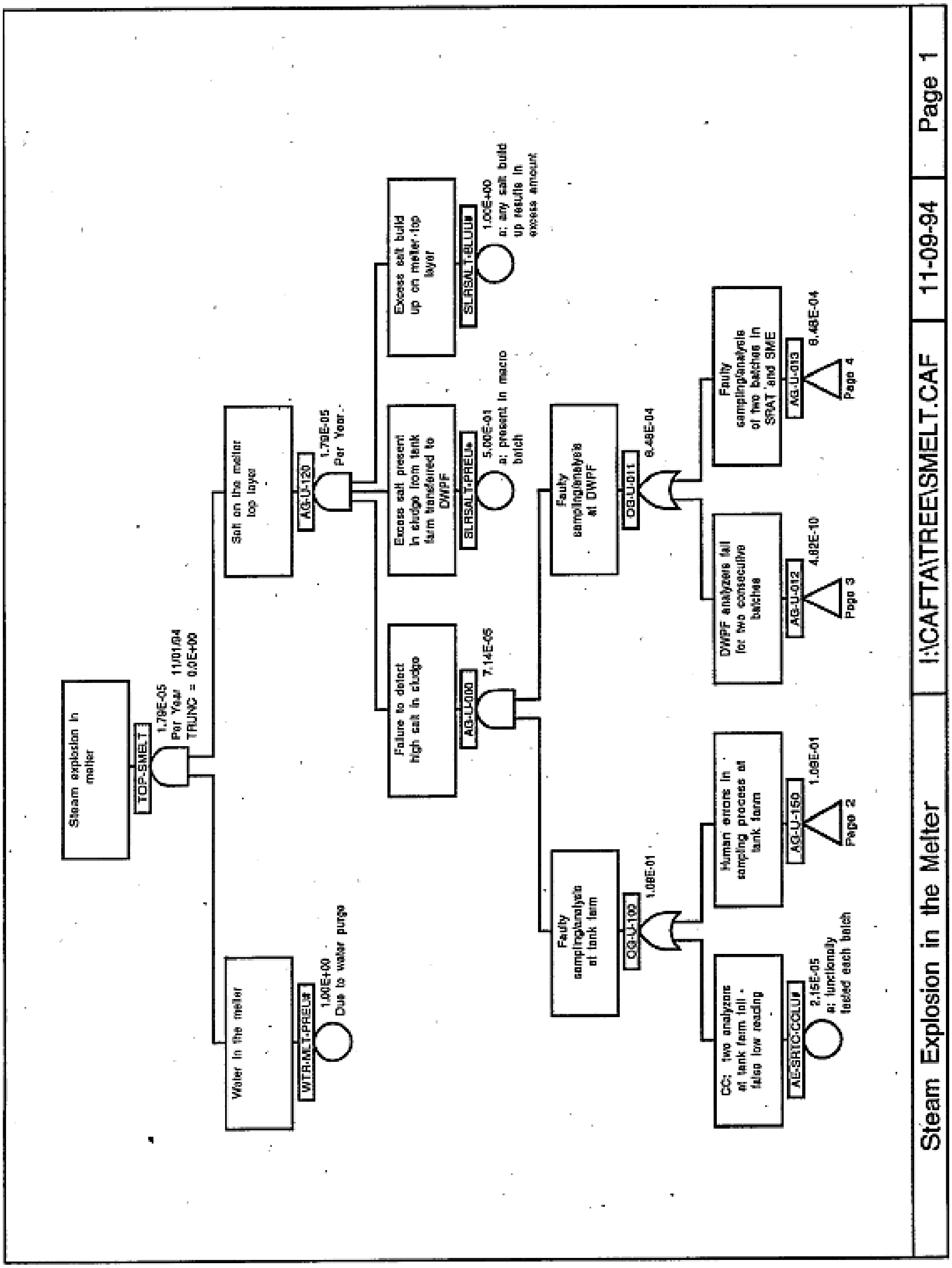
DEFENSE WASTE PROCESSING FACILITY APETS

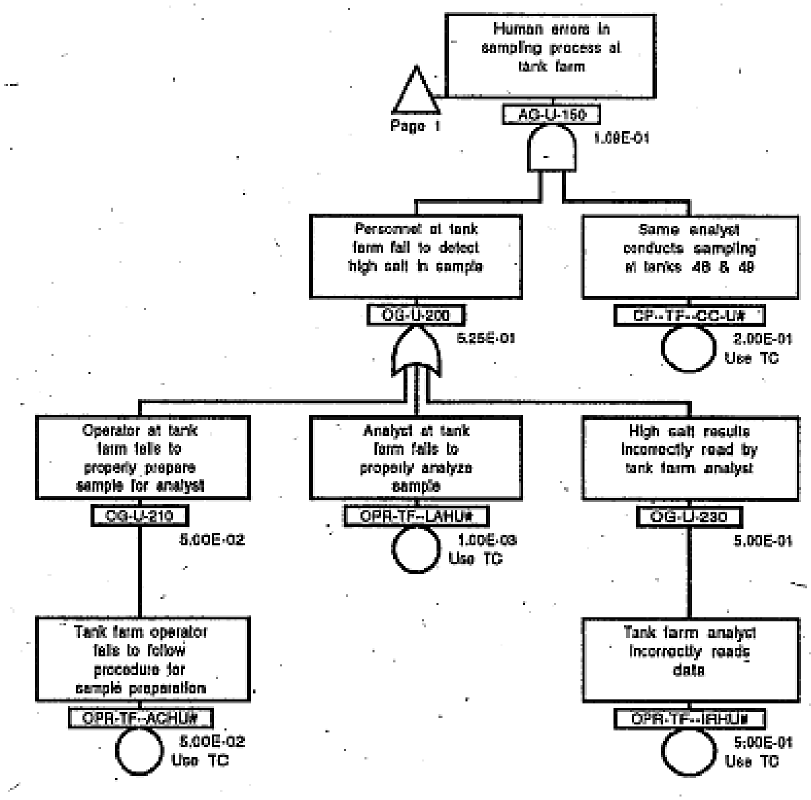
The following Appendix contains the 3 APETs used to determine the quantitative risk reduction potentially afforded by applying the developed performance measures to a nuclear chemical facility. All event trees are copied from the DWPF Event Tree Report (DWPF 1993).

The three events are as follows:

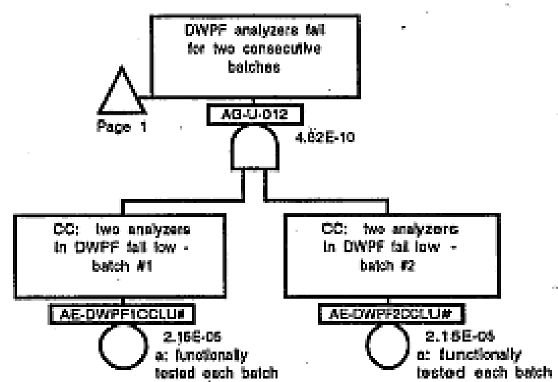
1. Steam Explosion in the Melter
2. Low Point Pump Pit in the Precipitate Pump Tank Explosion
3. Benzene Explosion in the Sludge Precipitate Tank (SPT)

E.1 Steam Explosion in the Melter APET

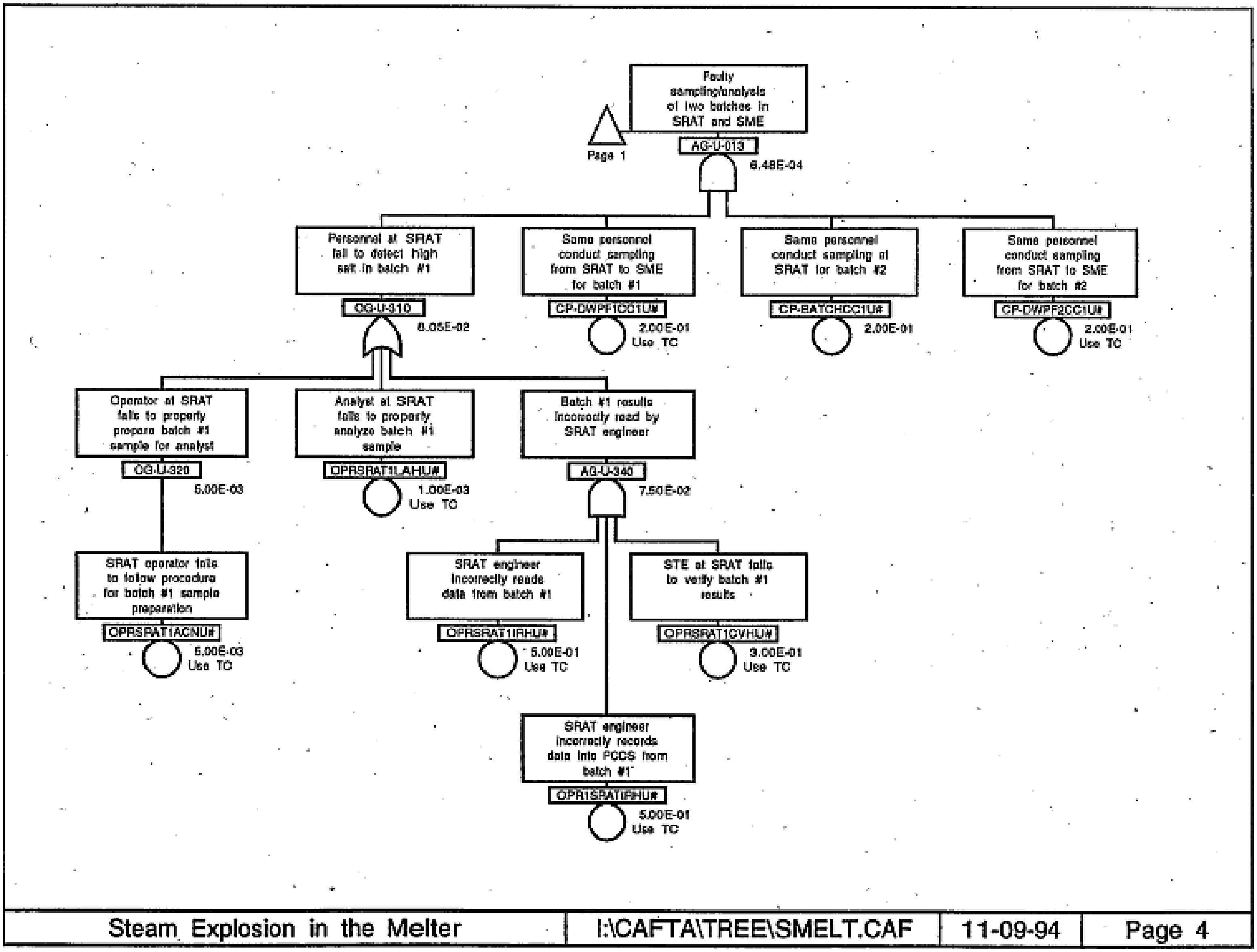




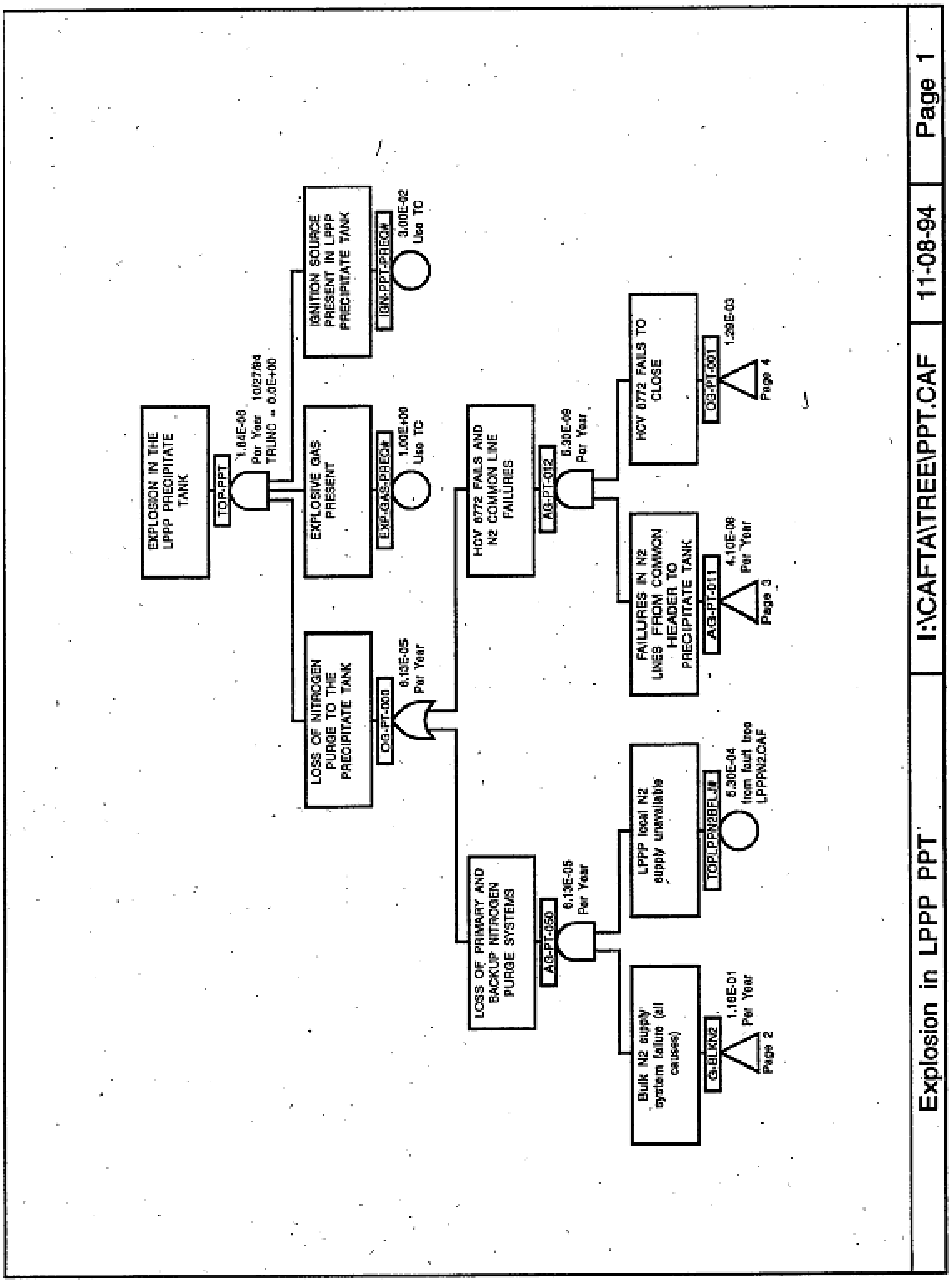
Steam Explosion in the Melter	I:\CAFTA\TREE\SMELT.CAF	11-09-94	Page 2

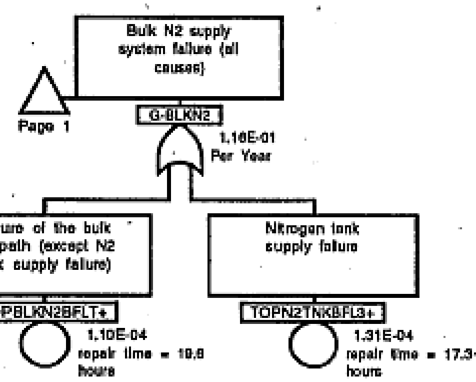


Steam Explosion in the Melter	I:\CAFTA\TREE\SMELT.CAF	11-09-94	Page 3

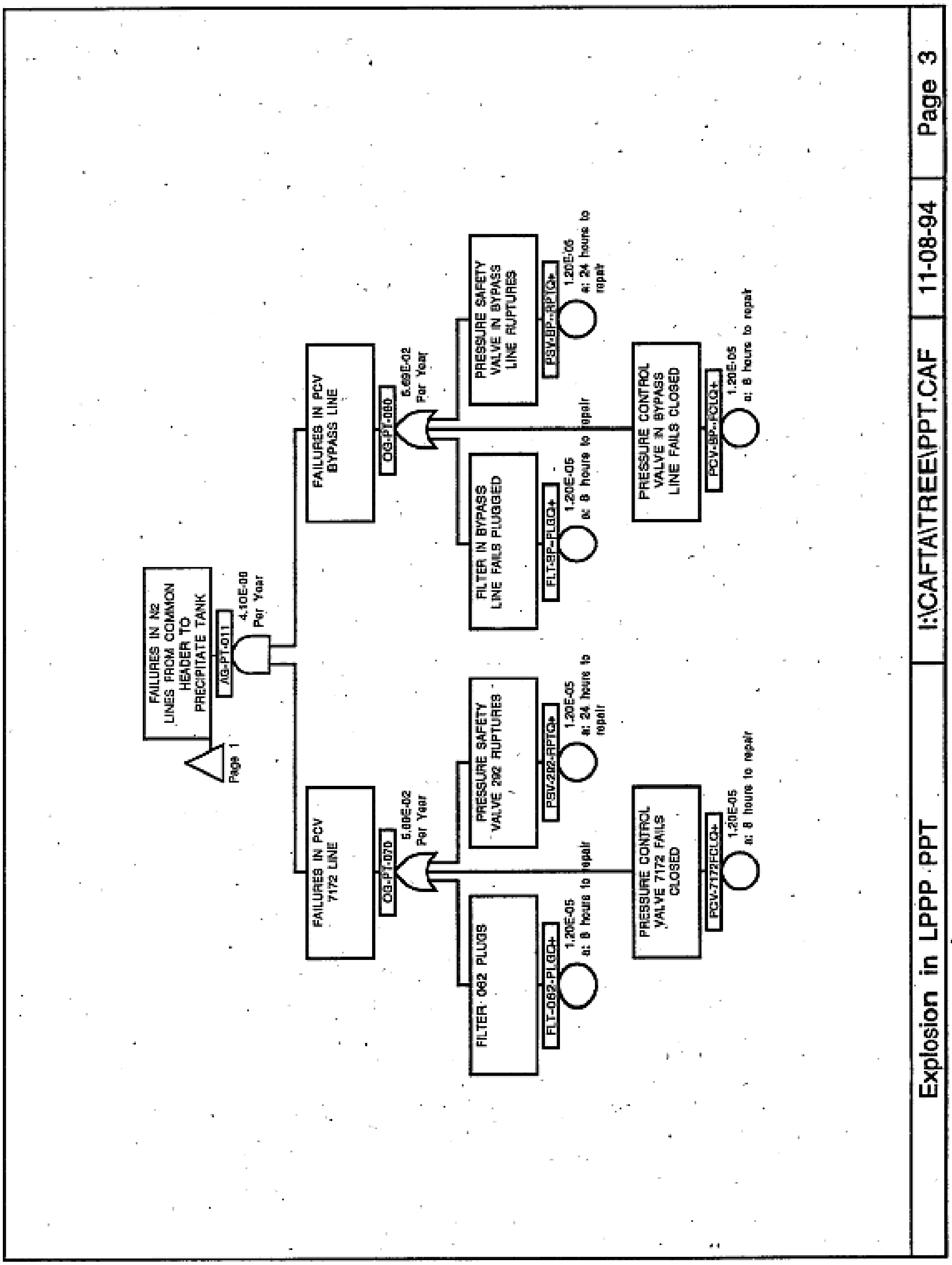

Faulty sampling/analysis of two batches in SRAT and SME
AG-U-013
6.48E-04
Page 1
Personnel at SRAT fail to detect high salt in batch #1
OG-U-310
6.05E-02
Same personnel conduct sampling from SRAT to SME for batch #1
CP-DWPF1CC1U#
2.00E-01
Use TC
Same personnel conduct sampling at SRAT for batch #2
CP-BATCHCC1U#
2.00E-01
Same personnel conduct sampling from SRAT to SME for batch #2
CP-DWPF2CC1U#
2.00E-01
Use TC
Operator at SRAT fails to properly prepare batch #1 sample for analyst
OG-U-320
5.00E-03
Analyst at SRAT fails to properly analyze batch #1 sample
OPRSRAT1LAHU#
1.00E-03
Use TC
Batch #1 results incorrectly read by SRAT engineer
AG-U-340
7.50E-02
SRAT operator fails to follow procedure for batch #1 sample preparation
OPRSRAT1ACNU#
5.00E-03
Use TC
SRAT engineer incorrectly reads data from batch #1
OPRSRAT1IRHU#
5.00E-01
Use TC
STE at SRAT fails to verify batch #1 results
OPRSRAT1CVHU#
3.00E-01
Use TC
SRAT engineer incorrectly records data into PCCS from batch #1
OPR1SRATIRHU#
5.00E-01
Use TC
Steam Explosion in the Melter
I:\CAFTA\TREE\SMELT.CAF
11-09-94
Page 4

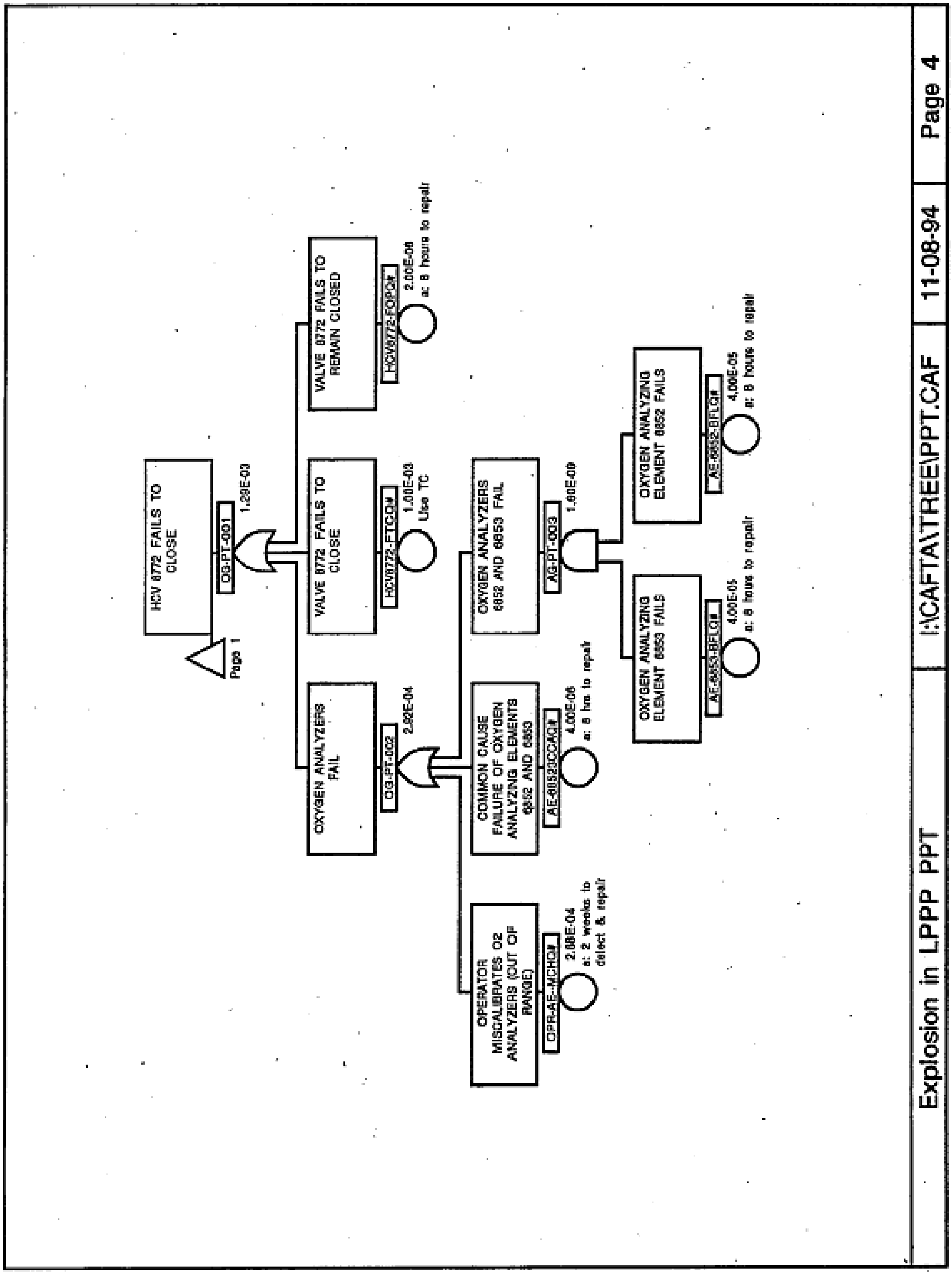
E.2 Low Point Pump Pit in the Precipitate Pump Tank Explosion APET



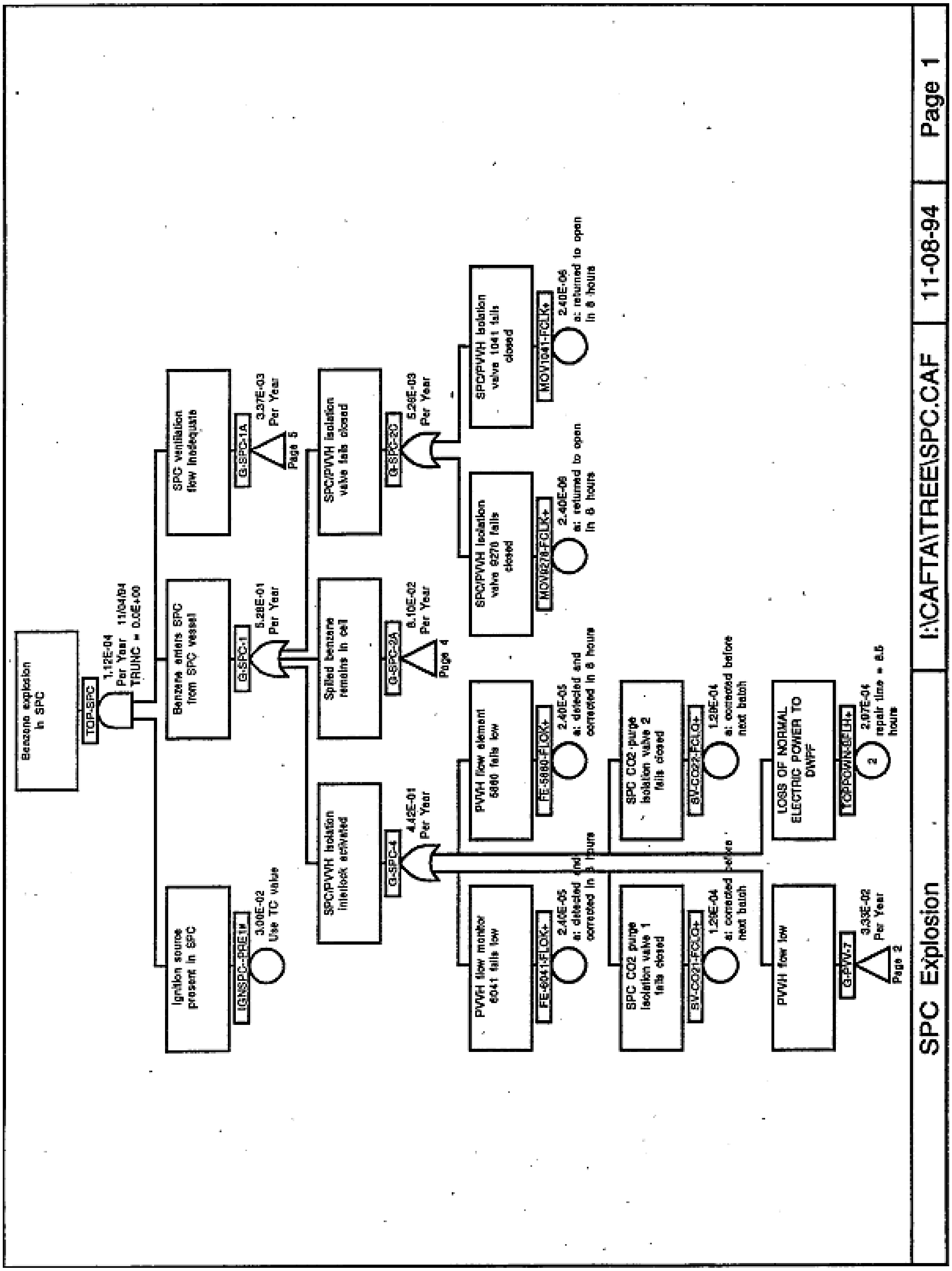


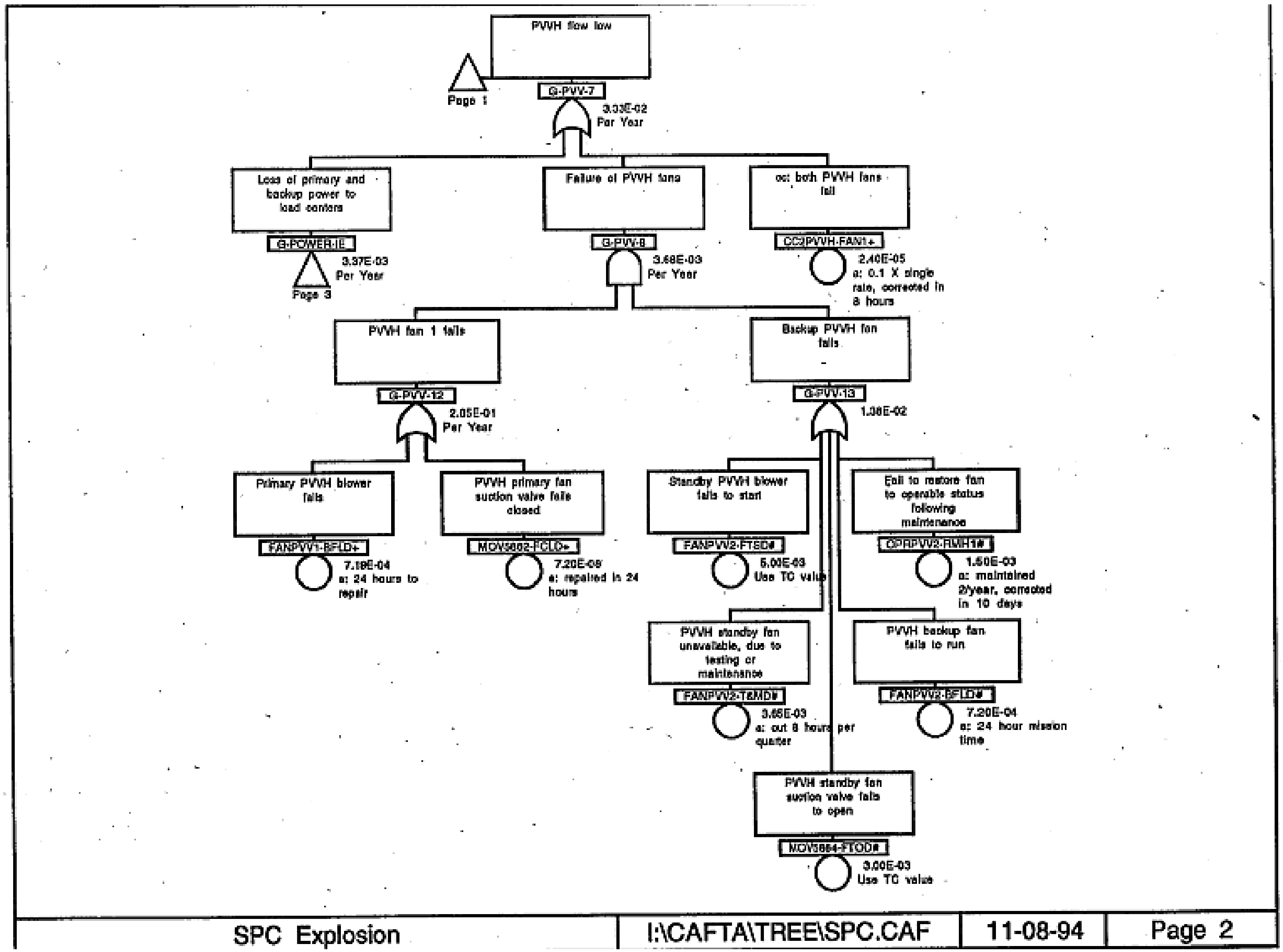
Explosion in LPPP PPT	I:\CAFTA\TREE\PPT.CAF	11-08-94	Page 2

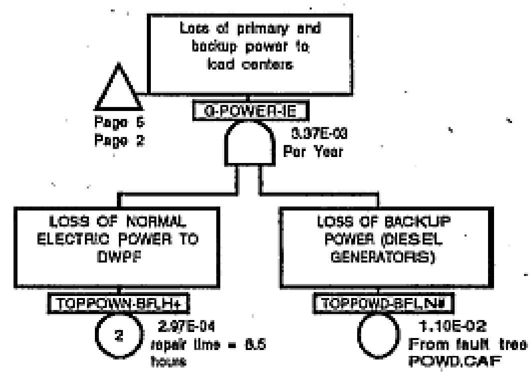

FAILURES IN N2 LINES FROM COMMON HEADER TO PRECIPITATE TANK
AG-PT-011
Per Year
Page 1
FAILURES IN PCV BYPASS LINE
OG-PT-080
5.69E-02 Per Year
PRESSURE SAFETY VALVE IN BYPASS LINE RUPTURES
PSV-BP--RPTQ+
1.20E-05
a: 24 hours to repair
FILTER IN BYPASS LINE FAILS PLUGGED
FLT-BP--PLGQ+
1.20E-05
a: 8 hours to repair
PRESSURE CONTROL VALVE IN BYPASS LINE FAILS CLOSED
PCV-BP--FCLQ+
1.20E-05
a: 8 hours to repair
FAILURES IN PCV 7172 LINE
OG-PT-070
5.60E-02 Per Year
PRESSURE SAFETY VALVE 292 RUPTURES
PSV-292--RPTQ+
1.20E-05
a: 24 hours to repair
FILTER 062 PLUGS
FLT-062-PLGQ+
1.20E-05
a: 8 hours to repair
PRESSURE CONTROL VALVE 7172 FAILS CLOSED
PCV-7172FCLQ+
1.20E-05
a: 8 hours to repair
Explosion in LPPP PPT
I:\CAFTA\TREE\PPT.CAF
11-08-94
Page 3


HCV 6772 FAILS TO CLOSE
OG-PT-001
1.29E-03
Page 1
OXYGEN ANALYZERS FAIL
OG-PT-002
2.92E-04
VALVE 6772 FAILS TO CLOSE
HCV6772-FTC@
1.00E-03
Use TC
VALVE 6772 FAILS TO REMAIN CLOSED
HCV6772-FOPO#
2.00E-06
a: 8 hours to repair
OPERATOR MISCALIBRATES O2 ANALYZERS (OUT OF RANGE)
OPR-AE-MCHO#
2.88E-04
a: 2 weeks to detect & repair
COMMON CAUSE FAILURE OF OXYGEN ANALYZING ELEMENTS 6852 AND 6853
AE-68523CCAQ#
4.00E-06
a: 8 hrs to repair
OXYGEN ANALYZERS 6852 AND 6853 FAIL
AG-PT-003
1.60E-09
OXYGEN ANALYZING ELEMENT 6853 FAILS
AE-6853-BFLQ#
4.00E-05
a: 8 hours to repair
OXYGEN ANALYZING ELEMENT 6852 FAILS
AE-6852-BFLQ#
4.00E-05
a: 8 hours to repair
Explosion in LPPP PPT
I:\CAFTA\TREE\PPT.CAF
11-08-94
Page 4

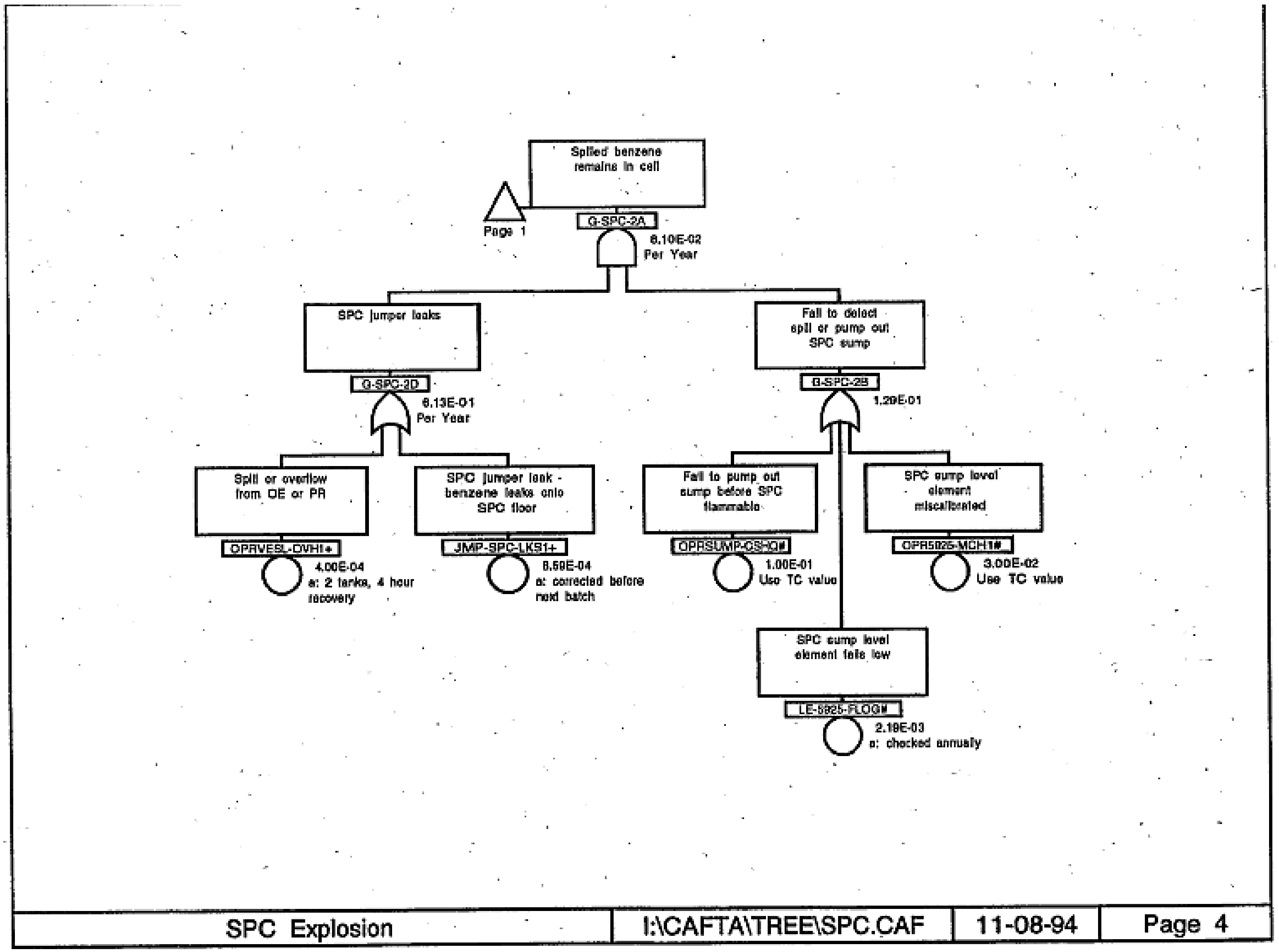
E.3 Benzene Explosion in the Sludge Precipitate Tank (SPT) APET

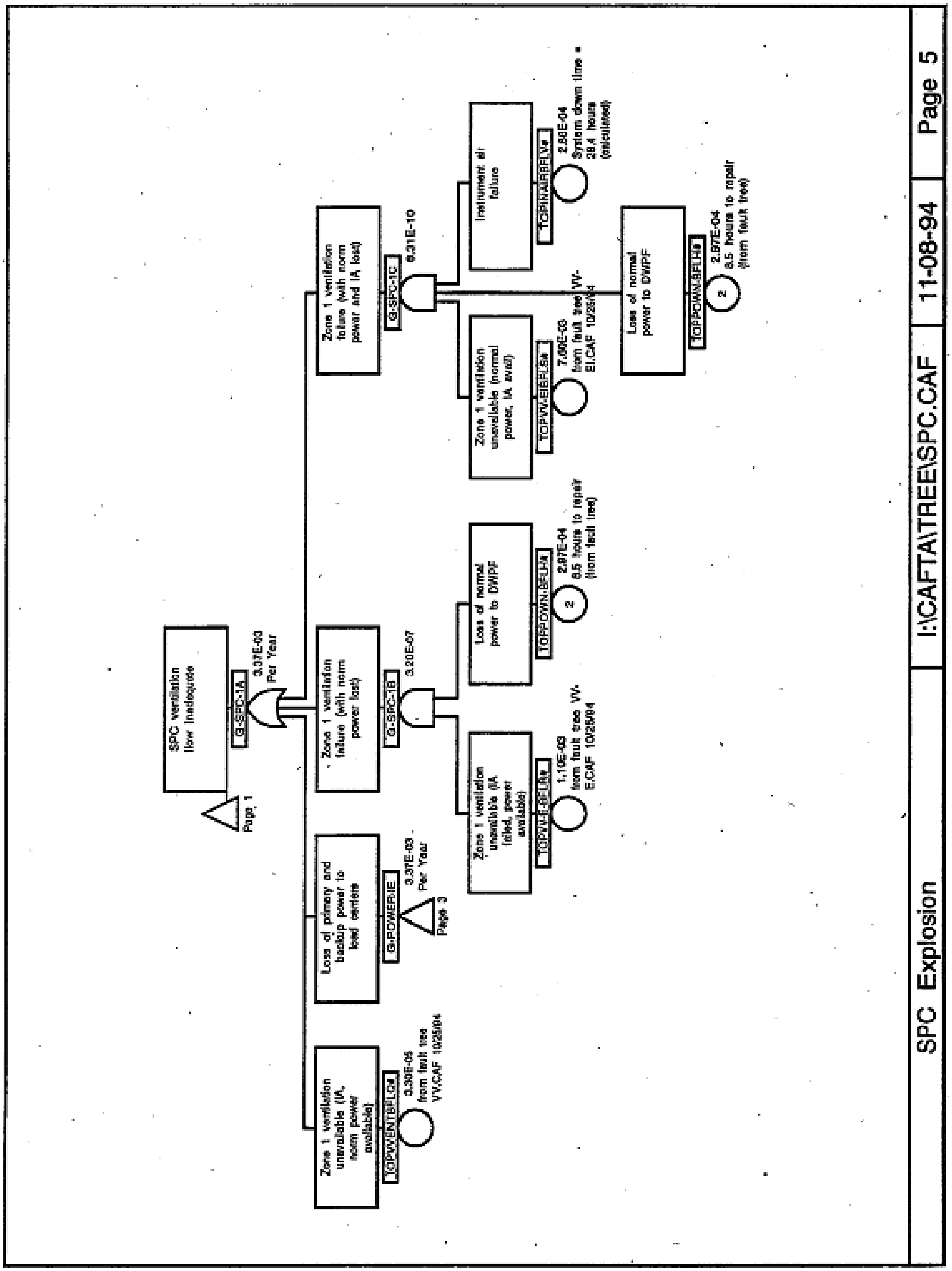



PVVH flow low
Page 1
G-PVV-7
3.33E-02
Per Year
Loss of primary and
backup power to
load centers
G-POWER-IE
3.37E-03
Per Year
Page 3
Failure of PVVH fans
G-PVV-8
3.68E-03
Per Year
cc: both PVVH fans
fail
CC2PVVH-FAN1+
2.40E-05
a: 0.1 X single
rate, corrected in
8 hours
PVVH fan 1 fails
G-PVV-12
2.05E-01
Per Year
Backup PVVH fan
fails
G-PVV-13
1.08E-02
Primary PVVH blower
fails
FANPVV1-BFLD+
7.19E-04
a: 24 hours to
repair
PVVH primary fan
suction valve fails
closed
MOV5662-FCLD+
7.20E-03
a: repaired in 24
hours
Standby PVVH blower
fails to start
FANPVV2-FTSD#
5.00E-03
Use TC value
Fail to restore fan
to operable status
following
maintenance
OPRPVV2-RMH1#
1.50E-03
a: maintained
2/year, corrected
in 10 days
PVVH standby fan
unavailable, due to
testing or
maintenance
FANPVV2-T&MD#
3.65E-03
a: out 8 hours per
quarter
PVVH backup fan
fails to run
FANPVV2-BFLD#
7.20E-04
a: 24 hour mission
time
PVVH standby fan
suction valve fails
to open
MOV5664-FTOD#
3.00E-03
Use TC value
SPC Explosion
I:\CAFTA\TREE\SPC.CAF
11-08-94
Page 2



SPC Explosion	I:\CAFTA\TREE\SPC.CAF	11-08-94	Page 3


Splled benzene remains in cell
Page 1
G-SPC-2A
6.10E-02
Per Year
SPC jumper leaks
G-SPC-2D
6.13E-01
Per Year
Fail to detect spill or pump out SPC sump
G-SPC-2B
1.29E-01
Spill or overflow from DE or PR
OPRVESL-OVHI+
4.00E-04
a: 2 tanks, 4 hour recovery
SPC jumper leak - benzene leaks onto SPC floor
JMP-SPC-LKS1+
8.59E-04
a: corrected before next batch
Fail to pump out sump before SPC flammable
OPRSUMP-CSHQ#
1.00E-01
Use TC value
SPC sump level element miscalibrated
OPR5925-MCH1#
3.00E-02
Use TC value
SPC sump level element fails low
LE-5925-FLOG#
2.19E-03
a: checked annually
SPC Explosion
I:\CAFTA\TREE\SPC.CAF
11-08-94
Page 4


SPC ventilation flow inadequate
G-SPC-1A
3.37E-03 Per Year
Page 1
Zone 1 ventilation unavailable (IA, norm power available)
TOPVVENTBFLDM
3.30E-05 from fault tree VV.CAF 10/25/94
Loss of primary and backup power to load centers
G-POWERIE
3.37E-03 Per Year
Page 3
Zone 1 ventilation failure (with norm power lost)
G-SPC-1B
3.20E-07
Zone 1 ventilation unavailable (IA failed, power available)
TOPVV-E-BFLH8
1.10E-03 from fault tree VV-E.CAF 10/25/94
Loss of normal power to DWPF
TOPPOWN-BFLH8
2
2.97E-04 8.5 hours to repair (from fault tree)
Zone 1 ventilation failure (with norm power and IA lost)
G-SPC-1C
6.31E-10
Zone 1 ventilation unavailable (normal power, IA avail)
TOPVV-EIBFLS8
7.60E-03 from fault tree VV-EI.CAF 10/25/94
Instrument air failure
TOPINAIRBFLV8
2.88E-04 System down time = 28.4 hours (calculated)
Loss of normal power to DWPF
TOPPOWN-BFLH8
2
2.97E-04 8.5 hours to repair (from fault tree)
SPC Explosion
I:\CAFTA\TREE\SPC.CAF
11-08-94
Page 5