DYNAMIC RISK ASSESSMENT USING ACCIDENT PRECURSOR DATA AND BAYESIAN THEORY

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ABSTRACT

To improve the safety of a process system, engineers use different methods to identify the potential hazards. Chemical processes involve handling of hazardous chemicals, which on release may potentially cause catastrophic consequences in terms of assets lost, human fatalities or injuries and loss of public confidence in the company. In spite of using endless end-of-the-pipe safety systems, tragic accidents such as BP Texas City refinery still occur. One of the main reasons of such rare but catastrophic event occurrences is lack of effective monitoring and modeling approaches that provide early warnings and help to prevent such events. Other reasons such as lack of criteria and/or assessment parameters and measures for detection of abnormal events may also have an important contribution.

One of the most popular methods used in the industry today is quantitative risk assessment (QRA) which quantifies the risk associated with a particular process activity by determining the likelihood of occurrence of an unwanted event and the consequences involved. One of QRA's major disadvantages is its inability to update risk during the life of a process. As the process/system operates, abnormal events will result in incidents and near misses. These events are often called accident precursors. A conventional QRA process is unable to use the accident precursor information to revise the risk profile.

Dynamic failure assessment is a new approach in process safety management, which enables the real time failure analysis of a process. Dynamic failure assessment has been used in the past by nuclear industries for accident likelihood estimation using accident precursors. Recently it has been successfully applied to process units to revise failure probabilities using incident and near miss data. In dynamic risk assessment, an extension of dynamic failure assessment, Bayesian and

joint probability theories are used to develop a predictive failure model for a given process. As the process/system operates and generates incidents and near misses, the accident occurrence probability is predicted using accident precursors and later multiplied with consequences to quantify real time risk.

In this thesis the dynamic risk assessment methodology is discussed in detail. First, potential accident scenarios are identified and represented in terms of an event tree, next, using the event tree and available failure data end state probabilities are estimated. Subsequently, using the available accident precursor data, safety system failure likelihood and event tree end state probabilities are revised. Finally, the updated probabilities are used in revising the risk profile of the process system.

Application of this tool is demonstrated by two case studies. The first case study is the process facility of an offshore oil and gas platform where the risk profiles of process units are determined over time. In the second case study dynamic risk assessment is applied to the BP Texas City refinery in order to demonstrate the predictive abilities of the tool. Dynamic risk assessment demonstrates the importance of a learning and predictive tool in risk assessment by verifying significant changes in system failure frequency in comparison with the conventional QRA approach.

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LIST OF SYMBOLS

Beta (α, β)	PDF of Beta distribution with α and β as shape parameters
Gamma (α, β)	PDF of Gamma distribution with α and β as scale and shape parameters
Binomial (n, p)	PMF of Binomial distribution with n as total number of trials and p as probability of success
Poisson (λt)	PMF of Poisson distribution with λ as average occurrence rate
θ	Probability of failure of a system
X	Real time data from the system
$\pi(\theta)$	Prior failure function
$l(X\|\theta)$	Likelihood function
$f(\theta\|X)$	Posterior failure function
$p(y_{N+1}\|Data)$	Probability of occurrence of an abnormal event within the next time interval
S	Cumulative number of abnormal events
N	Total number of time intervals
j	Number of releases in a time interval

Chapter 1

INTRODUCTION

1.1. Risk Assessment in Process Industries:

Risk assessment and management is an integral part of safety and loss prevention in process industries. Process industries often have large inventory of hazardous chemicals, and their process area is often highly congested with the presence of complex piping and various other equipment necessary for process operations such as high-pressure compression, separation, desulphurization, storage, and blending. These operating conditions are vulnerable to escalate a series of small mishaps into catastrophic events. To prevent such situations process industries have adopted the use of risk assessment within their facilities. Risk assessment is the determination of risk associated with a recognized hazard which includes determination of events that produce an accident, probability of those events and the consequences involved (Crawl & Louvar, 2002). Risk assessment looks into the key aspects of unwanted events such as the development of techniques to predict accidents, development of tools and models to analyse the potential consequences of an accident and the development of managerial strategies to minimize the risk involved in a potential accident scenario (Khan and Abbasi, 1998).

Risk assessment methodology is often categorized as *Qualitative* or *Quantitative* risk assessment. Qualitative risk assessment is mostly descriptive and it is used to identify the causes and consequences of unwanted events. Hazard and operability (HAZOP) and Failure Mode and Effects Analysis (FMEA) are among the most widely used methods in qualitative risk assessment. Quantitative risk assessment determines a quantitative value for risk which requires calculation of the two major components of risk, magnitude of potential loss (consequence) and occurrence probability of the unwanted event.

Quantitative risk assessment (QRA) comprises of three main steps each answering one of the three important questions of risk assessment:

1- What can go wrong and how? (Hazard identification)

2- What are the chances? (Probability assessment)

3- What are the probable outcomes? (Consequence assessment)

The last two steps are mostly referred to as risk estimation. Hazard identification is the detection of possible scenarios which have the potential of producing an accident. In other words, it is the identification of an event or a combination of events that may lead to an expected incident. Hazard identification may be applied using techniques such as process hazard checklist, hazard survey and safety reviews. "*Hazard identification and risk estimation are best done together. If hazard identification is done alone, it might lead to a process becoming "goldplated". This means that potentially unnecessary and expensive safety equipment and procedures are implemented because hazards of low probability and minimal consequences are identified*" (Crawl & Louvar, 2002). Risk estimation steps contain probability and consequence assessment which are the two elements of risk. Methods such as Fault tree analysis (FTA), Event tree analysis (ETA), Layer of protection analysis (LOPA) and Markov modeling (MM) are used in the probability assessment step of risk estimation.

ETA is among the most widely used methodologies in risk estimation which has also been adapted in this work. ETA is an inductive diagrammatic method which links the initial unwanted event to all its known consequences. ETA begins with the initiating unwanted event as the first branch of the tree and works toward the end-states considering the impact of failure or success of the safety systems involved. This method provides information on how a failure may occur with its probability of occurrence. Assuming availability of failure probabilities of each safety system in terms of deterministic values or probabilistic distributions, numerical values may be assigned to various branches of the event tree. This may be used to determine the probability of occurrence of any sequence of events beginning from the initiating event and leading to an end-state by simply multiplying the branch values in each sequence.

Consequence assessment requires the potential consequences to be presented in terms of numerical values. Consequence assessment has many approaches depending on its specific application. The quantification approach in this study is to transform all types of consequences to their equivalent dollar value amount. This may be done using consequence matrices which convert different types of consequences and severities into dollar value of damage.

Finally, risk may be calculated simply by multiplying the probability of occurrence of the unwanted event by the related potential consequences. If the risk value obtained is higher than the standard risk limit of the given process, design parameters will be changed to reduce the risk and the process will be validated by re-applying the QRA procedure until the process risk falls into acceptable regions.

1.2. Motivations and Objectives of Research:

QRA is a very common approach currently used by safety engineers in process industries with encouraging results. However statistics show that catastrophic accident still occur within the process facilities that seem to be preventable. Explosions and fires on March 23, 2005 at BP's Texas City refinery that killed 15 people and injured 180 (BP, 2005) and the most recent incident on 10 August 2008 in which heavy explosions occurred in Sunrise propane storage facility in Toronto, Ontario killing two and causing evacuation of thousands of people (CBC, 2008) are examples of such tragic incidents. This may be partly attributed to a major disadvantage of the conventional QRA approach which is its inability to capture variations in the risk profile as the process is subjected to upsets, deviations from normal operation, aging of assets, and human intervention. Also, risk control strategies in QRA are developed based on major events. Frequencies of such events are very low and thus not much information or scientific data are available to yield accurate results in risk analysis.

Dynamic failure assessment is a novel approach initially used in the nuclear industry which has recently been adopted in process industries (Meel, 2006). Dynamic failure assessment is a learning tool which uses incidents and near misses, herein referred to as accident sequence precursor (ASP) data, to update the frequency of occurrence of unwanted events. The objective of this research is to develop a *Dynamic Risk Assessment* approach by introducing the consequence assessment concept to the earlier proposed Bayesian probability updating mechanism and to validate its use by applying the model to sample case studies in the process industry.

1.3. Thesis Structure:

This thesis is categorized into seven chapters. The first chapter is a brief introduction on the concept of risk assessment in process industries followed by the motivations and objectives of this research. Chapter 2 gives a broad overview on the development of QRA strategies over the years and its significance and current practices in the process industry along with the novel and state-of-the-art methods developed recently by researchers as the literature review of this thesis.

Chapter 3 gives a detailed description of QRA, its methodology, steps and tools and advanced QRA application approaches. Chapter 4 introduces the dynamic risk assessment model. This chapter presents a detailed study on probability assessment and Bayesian inference along with consequence analysis in dynamic risk assessment and the development of the dynamic risk profile. The model is then validated by adapting data from an earlier case study on a nuclear power plant. Chapter 5 attempts to demonstrate the application of the dynamic risk assessment model by applying the tool to two case studies in process facilities. The first case study is an offshore oil and gas (OOG) process facility. Data from representative units of the OOG platform is used to develop the updated risk profile and to compare the units on the basis of safety and risk. The second case study demonstrates the tool's ability to foretell accidents by modeling the BP Texas City refinery incident. The objective of this case study is to evaluate whether this accident could have been predicted early on with reasonable confidence (in terms of likelihood of occurrence), if yes, how this information could be transformed so that it is effectively used in decision making. Chapter 6 concludes the study by a brief summary of results, conclusion and future scope of research in this area. Finally, Chapter 7 lists the references used in this thesis.

Chapter 2

LITERATURE REVIEW

Risk may be defined as a function of the potential scenario of accident, frequency of occurrence of the scenario and the consequences involved if scenario does materialize. (AICHE, 2000).

$$Risk = F(s, c, f)$$

Where s is the hypothetical scenario, c is the estimated consequence and f is the estimated frequency of occurrence of the scenario. Kaplan and Garrick (1981) have defined risk as a set of scenarios each with a designated occurrence probability and consequence. Risk assessment is the analysis of these events, probabilities and consequences. Contini, Amendal and Ziomas (1991) have presented a benchmark exercise undertaken with the aim of assessing the state-of-the-art techniques in risk analysis. A study of accident release and dispersion of ammonia from a pressurized tank was conducted by 11 different risk assessment teams worldwide.

Many techniques and methodologies have been proposed since the 70's for risk assessment (Khan & Abbasi, 1998). Quantitative and qualitative risk assessment are two types of the risk evaluation system (Ferdous, 2007). Qualitative risk assessment is mostly used to identify the hazards associated with a process and it is usually used as a preparation step for consequence analysis (Hauptmanns, 1988; Lees, 1996). Quantitative risk assessment analyses system risk in terms of numerical evaluation of consequence and occurrence probability of an unwanted event.

The first effort to apply quantitative risk assessment (QRA) was attempted by a team of specialists under the supervision of Norman Rasmussen for the US nuclear regulatory commission to estimate the public risks posed by commercial nuclear power plants (US NRC, 2007a). The result of this research was published in 1975 under the title *WASH-1400, 'The Reactor Safety Study'* which is mostly referred to as the "Rasmussen Report" (Levin and Rasmussen, 1984). After nearly 4 decades QRA has now become an advance and powerful tool in industries such that some initial methodologies have now been declared obsolete and are replaced by new and state-of-the-art techniques. QRA is now being extensively used in other industries such as the process industry. This tool plays an important part in ensuring the safety of equipment and personnel in dangerous working environments such as offshore platforms. A study by the UK Health and Safety Executive (2008) showed that process and structural failure incidents account for almost 80% of the risk to personnel offshore. The underlying causes of these incidents are mostly organizational and management factors. The probability of such events tends to be low, but the consequences are high in terms of loss of human life, capital assets, and damage to the natural environment. Quantitative risk assessment is one of the most important approaches used to prevent or reduce the impact of such incidents. Vinnem (1998) has presented a good overview of the application of QRA in offshore industries with emphasis on the importance of QRA in the development of regulations in various jurisdictions.

Research is still conducted in this area to improve the current methodologies used in QRA, Khan and Abbasi (1998) have presented a review on the available risk analysis techniques in chemical process industries among which HAZOP, FMEA, Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) can be listed as the most important. ETA and FTA are among the most widely used methods in QRA. ETA is one of the focuses of this study and therefore more effort to introduce this method will be made. ETA was originally used in the nuclear industry to determine the possible effect of failure in any safety system (Ramzan et al., 2007). Rausmussen

(1975) and Arendt (1986) used ETA in pre-incident and post-incident analysis of process systems. Researchers have also contributed to the ETA making the tool more efficient and easier to use. Papazoglou (1998) has developed an algorithm for the formulation of the basis of an automated computer assisted construction technique for an event tree, and recently Bucci et al. (2008) have presented an approach to construct dynamic ETs/FTs and address the concerns with the traditional ET/FT methodology.

Other efforts in the study of QRA in process industries may be seen in the work of Crawley and Grant (1997) which has proposed an offshore risk assessment screening tool that permits the risk assessment of many design options in a methodical manner. Khan and Amyotte (2007) have modeled BP Texas City refinery accident from a quantitative risk assessment perspective. Subsequently, Falck et al. (2000), Rettedal et al. (2000), Cross and Ballesio (2003) and Cleaver et al. (2003) have discussed the use of QRA in the design of an oil production/transportation system. De-Leon and Ortega (2004) have presented a risk analysis study of an offshore oil complex in Mexico. Yasseri and Prager (2004) have presented explosion recurrence models. Recently, Pula et al. (2005a, b, 2007) proposed a set of models for consequence assessment of oil and gas processing facility and Ferdous et al. (2007) have developed a reliable tool for probabilistic risk assessment. Both works are integral parts of QRA of a process facility.

Khan et al. (2002,a) integrated an analytical simulation and maximum credible accident analysis approach for analyzing safety management options for process facilities. This integrated approach determines exactly what safety measures, and level of sophistication is required to lower the risk to acceptable levels. It can also distinguish those units that cannot fulfill the safety requirements even after installing all conventional safety measures. This methodology is generally applicable at the design stage of a process. This approach could be revised to adopt real time abnormal situations (defined as deviations from the normal behaviour of the system described in the process procedures) or incident data to estimate updated probabilities of accident scenarios. The updated probabilities could be used in risk calculation. The revised risk would provide a more up to date status of the risk of process facilities.

Although QRA has proven effective so far in the industry it lacks an important element which is the interdependency of the risk function with time or in other words lack of learning from the process history. In the recent years researchers have been working on developing a more dynamic approach to QRA. This innovation was again initially attempted by the nuclear industry as it is among the most hazardous industries. Due to extreme consequences of incidents in this industry and the protective measures involved, accident frequency in the nuclear industry is very low and hence very little accident data is available for risk analysis; therefore, an approach to use incidents and near misses as updating tools was developed (Bier and Mosleh, 1990; Bier and Yi, 1995). Early examples of this approach may be seen in the works of Cooke and Goossens (1990) and Johnson and Rasmuson (1996), Kirchsteiger (1997). This methodology is recently being developed in the process industry. Cepin et al. (2002) have developed a method which represents the extension of the classic fault tree with time requirements while Boudali et al. (2005) have defined a discrete-time Bayesian Network reliability formalism and demonstrated its capabilities from a modeling and analysis point of view. Sonnemans et al. (2003) have investigated the possibility of predicting 17 accidents in the Dutch chemical industry with the use of double or single loop control analysis and Mili et al. (2009) has demonstrated the possibility to use FMECA in a dynamic environment.

Dynamic failure assessment is a new approach that enables the real time failure analysis of a process. Meel and Sieder (2006) are pioneers in successfully implementing this approach to revise process deviations and failure analysis in chemical process industries. This approach combines Bayesian and joint probability theories to conduct dynamic failure assessment and to develop a predictive model of a given process (Meel et al. 2007). A similar methodology was recently used by Yun et al. (2009) to conduct a risk assessment analysis on LNG terminals. Kalantarnia and coworkers have used the dynamic failure assessment model to analyze a chemical process unit and joint probability theory as a predictive model (Kalantarnia et al. 2008). A similar work by these authors analyses the risk profile of an offshore oil and gas process facility (Kalantarnia et al. 2009).

Dynamic failure assessment uses Bayesian Inference as the updating mechanism. Bayesian Inference is a direct application of the probability theory which uses the basis of conditional probability in Baye's theorem (Bayes, 1763; Robert, 2001) to describe the uncertainty of a parameter. Bayesian theory has been gaining increasing attention in the recent years. In process industries many contributions have been made by researchers in this area. Won and Modarres, (1998) have developed an improved Bayesian method for diagnosing the partial failures of equipment in process plants, also Mehranbod et al. (2005) have presented a sensor fault detection and diagnosis method using Bayesian Belief Networks (BBNs) for processes in transient or steady-state operations. In another study, Chen et al. (2004) have carried out a Bayesian estimation of state variables and model parameters of chemical processes using sequential Monte-Carlo sampling. Contributions have also been made in other areas such as reliability engineering, a Bayesian reliability assessment method has been proposed by Wu (2004) that assigns prior distributions to fuzzy parameters. Furthermore, a Bayesian approach has been used by Jun et al. (1999) to predict system failure rates by criticalities using event trees for a simple hypothetical model. However, the failure rates are assumed to be the same under different accident criticalities. Also, a method to analyze dependencies in event trees, using copula and Bayesian theory along with accident sequence precursor data, has been proposed for nuclear plants by Yi and Bier (1998).

This tool may be applied to update failure probabilities in QRA by incorporating new data to revise earlier failure probability estimates. In simple words, the resulting failure probability is not a new value but an improvement of the earlier estimate with better confidence. In process safety, end events are rare to occur thus it is difficult to estimate their frequency based on historical data; however, near miss and incidents occur more frequently. This approach makes use of the near miss and incident data, to update failure probabilities of a process system. The updating method is used to revise the failure frequencies which in turn add confidence to the QRA. QRA without improvements and updates become obsolete over time as failures, degradation and occurrence of abnormal events cause changes in the behavior and characteristics of the system.

Dynamic failure assessment can be used as the foundation of a systematic tool which is capable of producing the real time risk profile of a given process. This may be achieved by incorporating consequence analysis with failure assessment which is attempted in this study.

Chapter 3

QUANTITATIVE RISK ASSESSMENT

Quantitative risk assessment (QRA) determines a quantitative measure of risk in terms of likelihood of occurrence and potential consequences of an unwanted event. QRA generally consists of three main steps: hazard identification, probability assessment and consequence assessment. The last two steps are known as risk estimation steps. Figure 3-1 shows the conventional QRA approach graphically.

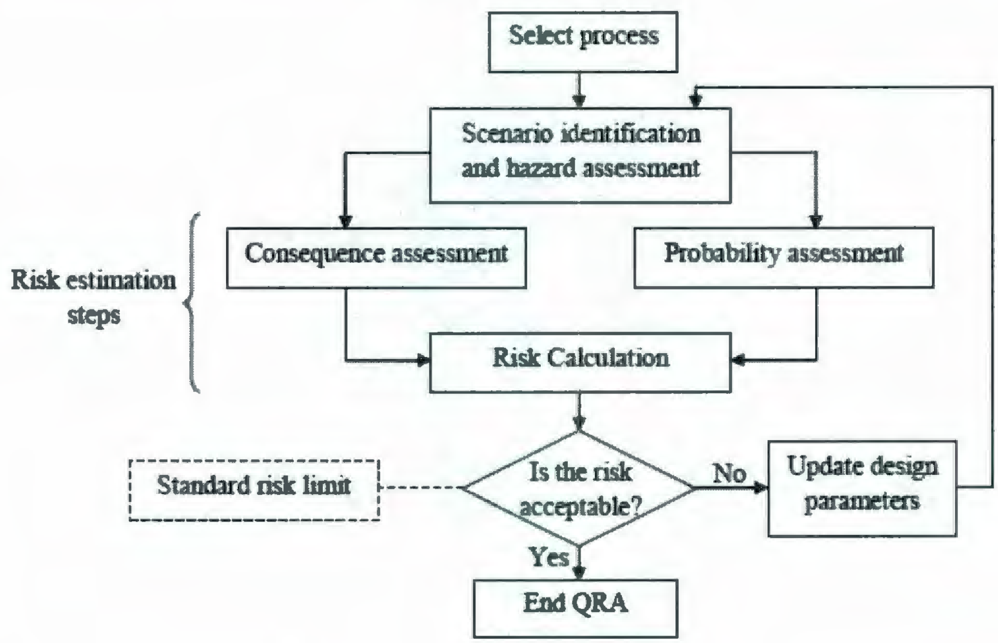

Figure 3-1. Conventional QRA procedure

3.1. Hazard Identification

Hazards are defined as events or processes that have the potential of creating an accident. Hazard identification is a key step in identifying the potentially hazardous elements of a process and the accident scenario in which they are likely to be involved. After the hazards have been identified, the scenarios in which hazard may potentially cause an accident are identified. This step is referred to as hazard identification. In this step the initial event causing the incident, the safety systems involved and the possible outcomes including the type of failure are determined. Hazard identification may be conducted independently from the risk estimation steps; however, best results are obtained when they are done together (Crawl & Louvar, 2002). One of the most frequently used hazard identification methods is HAZOP.

Hazard and operability (HAZOP) study is an approach that involves brain storming in a controlled environment to consider all possible ways an incident could occur. To conduct this study detailed information about the selected process must be available. The HAZOP committee use predefined guide words to determine if any combination of process parameters and guide words are valid. Subsequently, possible causes, control systems and potential consequences of the incident are investigated and recommendations are made. Other common methods of hazard identification are process hazard checklist, hazard survey and safety reviews.

3.2. Probability Assessment

Probability assessment is an important part of risk estimation which deals with the likelihood of event occurrence. The likelihood of an unwanted event usually corresponds to the probability of a failure in process industries. Failure probability used in risk assessment may be either a single value or in terms of a probability distribution taking into account the uncertainties involved. In order to better understand the probability assessment step, it is essential to briefly review the concept of probability theory.

3.2.1. Probability Theory

Probability theory is a widely accepted technique to express uncertainties in a parameter. In many cases, estimating the probability of an event may be the most difficult part of the computation. Randomness in an event means that more than one outcome is possible or in other words the outcome is somewhat unpredictable. Possible outcomes of events are a range of observed values in which usually some occur more frequently than others. To analytically quantify this randomness probability density functions (PDF) are used. A PDF does not directly provide information on probability but indicates the nature of the randomness (Haldar et al., 2000). Any mathematical model satisfying the properties of a PDF may be used to quantify uncertainties in a random variable. These mathematical models are known as probability distributions. Depending on the nature of the variable (continuous or discrete) many types of distributions exist from which various distributions are commonly used in a specific profession to model the probability of an event. In this chapter the probability distributions used for this study are briefly reviewed.

3.2.1.1. Continuous Random Variables

- **Beta distribution:** Beta distribution displayed as *Beta (α, β)* is often used to describe uncertainty about the probability of an event occurrence in which a number of trials n have been made with a number of recorded success s. The PDF of this distribution is:

$$f(x) \propto x^{\alpha-1}(1-x)^{\beta-1}$$

- **Gamma distribution:** Gamma distribution, *Gamma (α, β)*, models the time requires for α events to occur with a mean time between events of β. The PDF function may be written as:

$$f(x) \propto x^{\alpha-1}e^{(-\frac{x}{\beta})}$$

3.2.1.2. Discrete Random Variables

- **Binomial distribution:** Binomial distribution, *Binomial (n, p)*, shows the number of success from n independent trials where there is a p probability of success in each trial. The function indicating the nature of randomness in discrete variables is a probability mass function (PMF). The PMF of a Binomial distribution is:

$$f(x) \propto p^x(1-p)^{n-x}$$

- **Poisson distribution:** The Poisson distribution, *Poisson (λt)*, models the number of occurrences of an event in a time t where λt is the average number of occurrence of the event. The PMF of the Poisson distribution may be written as (Vose, 2003):

$$f(x) \propto e^{-\lambda t}(\lambda t)^x$$

3.2.2. Probability Assessment Methods

The most common methods in probability assessment are event tree analysis (ETA) and Fault Tree Analysis (FTA).

3.2.2.1. Event Tree Analysis

An event tree is a graphical representation of the logic model that identifies and quantifies the possible outcomes following an initiating event. In order to construct an event tree the following steps need to be taken:

Step 1: Identify the initial unwanted event as the first branch of the tree.

Step 2: Identify the safety systems involved in the potential scenario caused by the initial event and their failure probabilities.

Step 3: Construct the event tree based on all possible scenarios of failure or success of each safety system.

Step 4: Identify all end-states and calculate their occurrence probabilities by multiplying the branch values in each sequence from the initiating event to the last safety system. Figure 3-2 shows the schematics of an event tree.

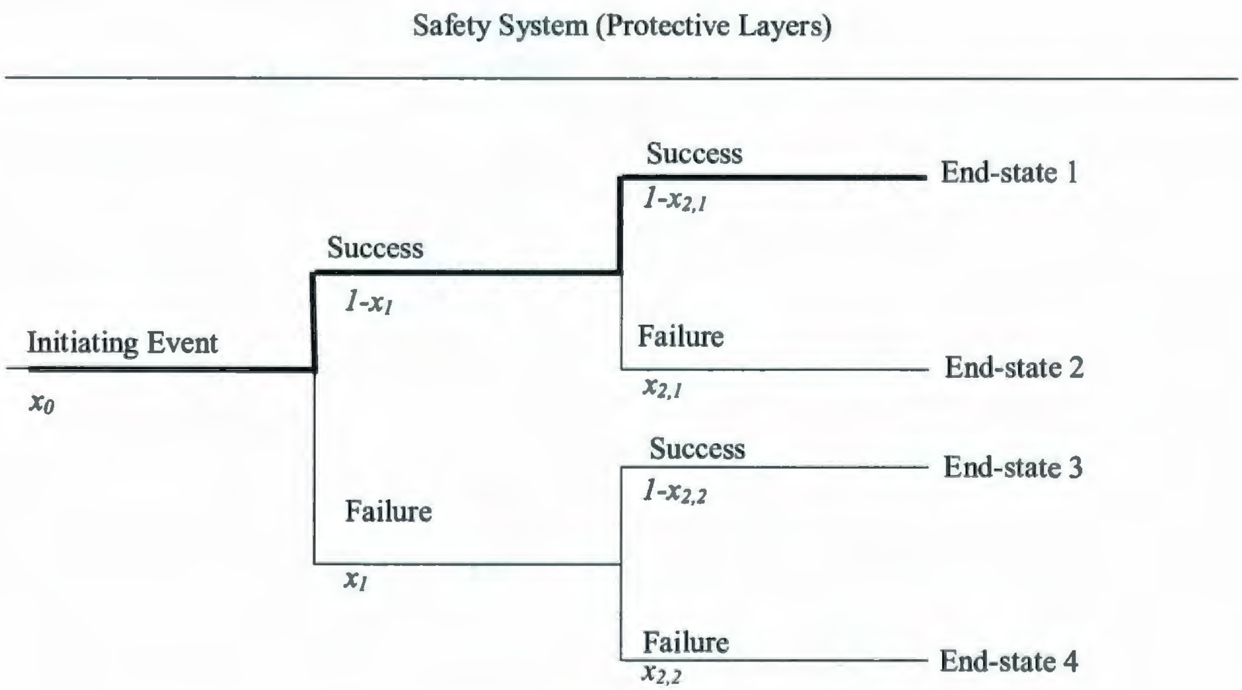

Figure 3-2. Schematics of an even tree

Figure 3-2 shows that calculating end-state probabilities is easily done via the event tree by multiplying the branch values leading to that end-state. For example, the occurrence probability of end-state 1 may be obtained simply by following the highlighted branches:

$$P(End - state\ 1) = x_0(1 - x_1)(1 - x_{2,1})$$

The example in Figure 3-2 is very simple while for large processes an event tree analysis could be very complicated and time consuming.

3.2.2.2. Fault Tree Analysis (FTA)

Fault tree analysis is a deductive graphical design technique which is structured in terms of events rather than components. This approach identifies ways in which hazards may lead to accidents. This tree begins with an accident as the top branch and works backwards to reach the basic causes of the accident. This diagram uses logic gates to express logical relationships between events. The most common gates used in a fault tree are AND and OR gates. AND gate requires all events to combine to yield the top event; however, in the case of the OR gate occurrence of at least one event is sufficient to lead to the top event. The following steps are required for the development of a fault tree:

Step 1: Define the system and identify the top event.

Step 2: Using appropriate logical gates construct the fault tree starting from the top event and working backwards to the intermediate and finally the basic events.

Step 3: Perform quantitative evaluation by assigning failure probabilities to the basic events and calculating the probabilities of the intermediate and top events (Ebeling, 2000).

Figure 3-3 shows the schematics of a fault tree. Using Boolean algebra the relation between the top event and the basic events in Figure 3-3 may be written as:

$$A = B \cup C = (D \cap E) \cup C$$

In which *A, B, C, D* and *E* are occurrence probabilities of each event. Assuming independency between the events, by applying the properties of set theory to the Boolean equation we will have:

$$A = (D \times E) + C - (D \times E \times C)$$

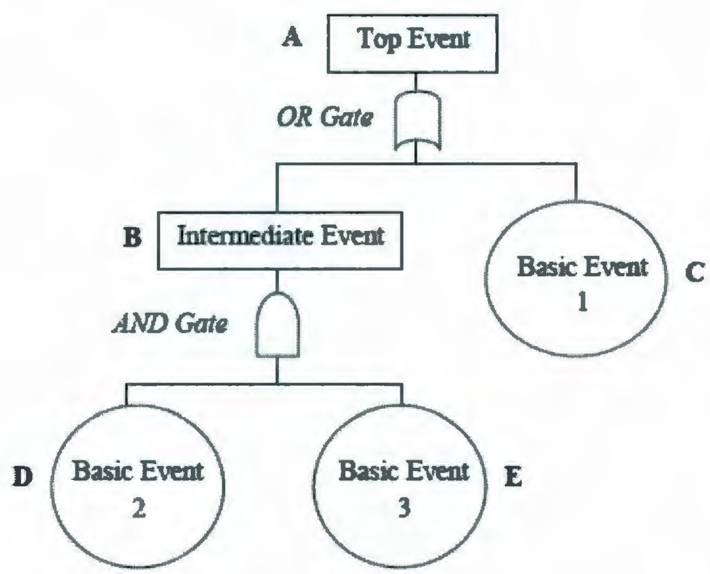

Figure 3-3. Schematic of a fault tree

3.3. Consequence Assessment

Consequence is defined as "*a measure of the expected effects of the results of an incident*" (Crawl & Louvar, 2002). Figure 3-4 shows a generalized algorithm to categorize the consequences of an incident.

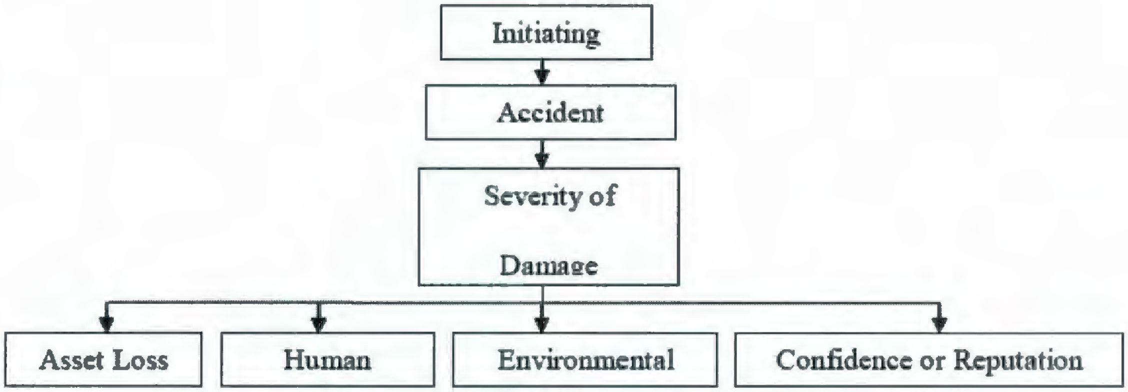

Figure 3-4. Generalized algorithm for consequence analysis

Consequence assessment describes the extent of damage in terms of asset loss, human fatality, environmental loss and confidence or reputation loss. The most common incident in process industries are loss of containment and releases which can be quantified using toxic release and dispersion models. Consequences of other common incidents such as fire and explosion may be determined via fire and explosion modelling.

In order to incorporate the consequences of an accident into the risk profile, those consequences can be presented in quantifiable terms such as dollar value. As briefly explained in Chapter 1, this conversion may be done using consequence severity matrices. Table 3-1 shows one example of such matrix developed for the process industry.

It may be seen from Table 3-1 that the three categories of human fatality, environmental loss and confidence or reputation loss may be converted into their equivalent dollar value of damage according to the severity of loss. With the severity class known, the dollar value of damage may be directly integrated into the risk profile to yield the risk associated with a hazard.

After both the frequency of occurrence of the unwanted event and the potential consequences are determined the next step in risk estimation is to develop the process risk by multiplying the two parameters above.

The final step of QRA is to compare the risk value obtained to the predefined risk limit. If the risk value exceeds that limit than the design parameters must be changed to reduce frequency of failure of to mitigate the consequences so that the revised risk would fall within the acceptable region of the risk limit.

Severity Class	Asset Loss	Human Loss	Environmental Loss	Confidence or Reputation Loss
1	<10K	One minor injury needing first aid attention	Around the operating unit area, Easy recovery and remediation	Get noticed in plant
2	10 k to 100K	One or two injuries requiring hospital attention however no threat to life	Within plant, Short term remediation effort	Get attention in the industrial complex. Information shared with neighboring units
3	100K to 1 million	Multiple major injuries, potential disabilities, potential threat to life	Minor offsite impact, Remediation cost will be less than 1 million	Local media coverage
4	1 to 10 million	One fatality and/or multiple injuries with disabilities	Community advisory issued, Remediation cost remain below 5 million	Regional media coverage a brief note on national media
5	> 10 million	Multiple fatalities	Community evacuation for longer period, Remediation cost in excess of 5 million	National media coverage, Brief note on international media

Table 3-1. Consequence severity matrix
(Developed with the feedback of loss prevention group of a major oil and gas company)

3.4. Advance QRA applications

As further research is being conducted in the field of QRA new and advance approaches are developed to facilitate the application of each three step of QRA in the industry. Some of these methods are based on a combination of various techniques previously developed. A few of these tools are listed below:

1- MCAA: Maximum Credible Accident Analysis is an approach for forecasting an accident in a process plant. MCAA comprises of four main steps: hazard identification, development of credible accident scenarios, assessing the damage likely to be caused by those scenarios and determining the most credible accident scenario (Khan and Abbasi, 1998).

2- PSA: Probability Safety Analysis provides a framework for hazard identification and risk estimation. It also provides a basis for safety related decision making. PSA consists of seven major steps: hazard identification, accident sequence modelling, data acquisition and parameter estimation, accident sequence quantification, hazard substance release categories, consequence assessment and integration of results (Khan and Abbasi, 1998).

3- SCAP: Safety, Credible Accidents and Probability fault tree analysis is new methodology which integrates Analytical Simulation (a new methodology for fault tree analysis proposed by Khan and Abbasi in 2002a) and maximum credible accident analysis. The methodology intends to identify and quantify the presence of hazards in an industry, predict the impact of likely accidents in and around the industry, recommend safety measures and reassess the hazards by incorporating the recommended safety measures. Hence, it allows one to work out exactly what safety measures, of what sophistication, can decrease the hazard to an acceptable level (Khan et al., 2002,a).

There are other advance tools and techniques which one may choose depending upon the complexity of the system.

Chapter 4

DYNAMIC RISK ASSESSMENT

Dynamic risk assessment is a new approach which uses the fundamentals of quantitative risk assessment and real time data from the process to develop a risk profile for the system. The special feature of this profile is the ability to simulate the risk of the system as a function of abnormal events occurring over its lifetime. Therefore the risk profile obtained using dynamic risk assessment approach is indirectly a function of time.

Depending on the rate of event occurrence in a system the current risk profile could be significantly different from the original risk of the process calculated at the design stage. This shows that the design stage data may not be very reliable after the process is subjected to deterioration, fatigue and possibly human intervention.

Risk has two major parameters which are failure probability and consequence. Failure probability in this methodology is continuously updated and changes every time an accident sequence precursor (ASP) such as incidents and near misses occur in the system. The resulting risk profile developed after the failure probability update is referred to as the posterior risk. At the design stage of the process the original failure probability function, herein denoted as the prior function, is determined in terms of a probability distribution due to the uncertainties involved. With the ASP data available, Bayesian theory is used to determine the posterior failure probability in the form of a probability distribution. Subsequently, the posterior risk profile is obtained simply by multiplying the new failure probability function by its related consequence.

Finally using both Bayesian and joint probability theories a predictive model is developed which can predict the number of expected abnormal event occurrences within the next time interval.

4.1. Methodology

Figure 4-1 shows graphically the step by step procedure of applying the dynamic risk assessment methodology. Dynamic risk assessment may be implemented to a selected unit in five steps:

Step1: Scenario identification: This step identifies the most likely scenarios, types of failures and end-states associated with an incident. After determining the scenario, the initiating abnormal event and all safety systems serving as protective layers to reduce or eliminate the effect of that event are identified. This information is then used to form the event tree as discussed previously in Chapter 3. This event tree will show the relations between failure or success of each safety system with the possible end-states.

Step2: Prior function calculation: Using design stage data the initial or prior failure probabilities of each safety system are calculated in terms of probability distributions from plant specific data and expert judgment. Given that in event tree analysis a single value is used as failure probability in each branch and not an entire distribution, the mean value of the PDF is selected as the representative value of the distribution to be used in the event tree to obtain end-state probabilities.

Step 3: Formation of the likelihood function: Incident and near misses are used to form the likelihood function which is later used to update the prior failure function. The data recorded from the system are number of process upsets, shutdowns and other forms of failures which are all defined in the event tree. These values are recorded every year and are used in the cumulative form to develop the likelihood function.

Step 4: Posterior function calculation: Bayesian theory is used to calculate the posterior function using subjective prior knowledge and real time data from the system which are mathematically presented in the form of the prior and likelihood functions. This step will yield the posterior failure probabilities of all the safety systems and end-states.

Step 5: Consequence analysis: Consequence analysis is conducted on a selected scenario to estimate the potential consequences of all possible end-states using the methodology described in Chapter 3. The consequences obtained in this stage are presented in dollar value amount.

These five steps develop the two main elements of risk, failure probability and consequence. Therefore, the posterior risk profile is obtained by multiplying the two elements.

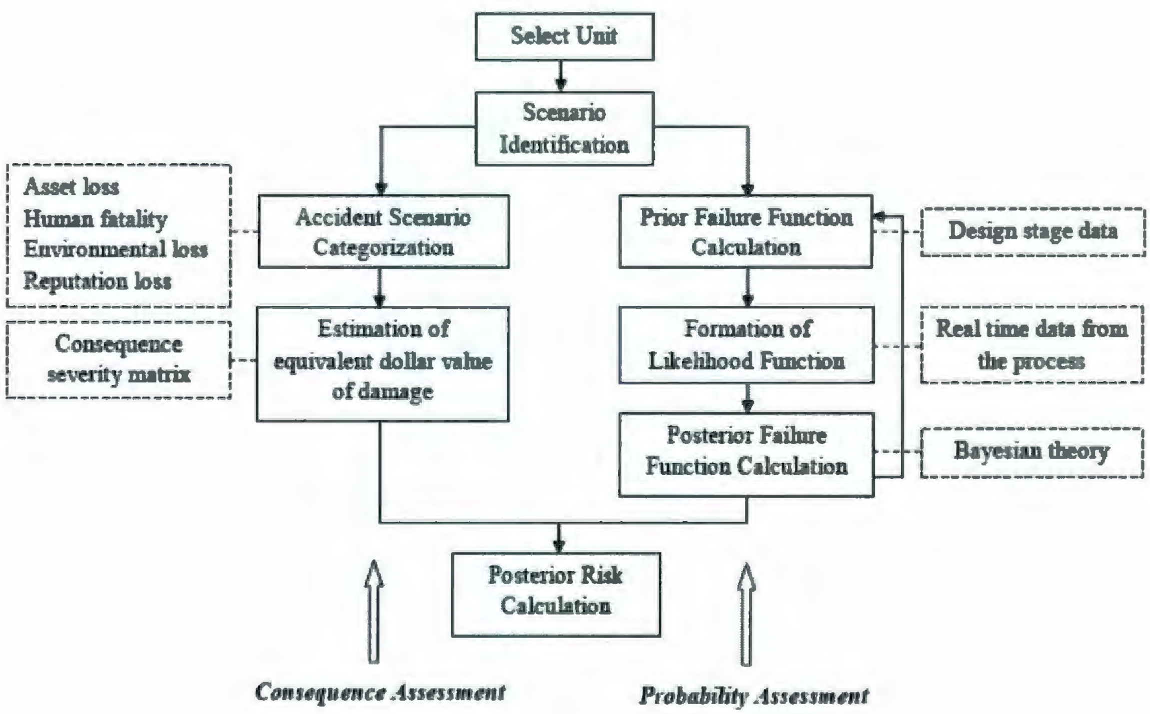

Figure 4-1. Dynamic Risk Assessment Methodology

4.2. Bayesian Inference

Bayesian inference is a powerful technique based on Bayes' theorem which uses data to improve the estimation of a parameter. There are mainly three steps involved: Determining the prior function, finding the appropriate likelihood function and calculating the posterior function.

Baye's theorem represents the conditional probability of occurrence of event A given that event B has already occurred. This probability may be presented as:

$$p(A_i|B) = \frac{p(B\,|\,A_i)p(A_i)}{\sum_{i=1}^{n} p(B|A_i)p(A_i)}$$

"*Bayesian inference mathematically describes a learning process*" (Vose, 2000). The first step of this methodology is selecting a prior function which is mostly chosen subjectively based on expert opinion; this function is modified later after data is collected from the system as evidence of its behaviour. The equation below is based on Bayes' formula; however, the notations are changed to what is often used in Bayesian inference.

$$f(\theta\,|\,X) = \frac{\pi(\theta)l(X\,|\,\theta)}{\int \pi(\theta)l(X\,|\,\theta)}$$

In dynamic failure assessment, Bayesian theory is used to improve failure probabilities. The parameters in the above equation are (Vose, 2000):

- $\pi(\theta)$- The prior distribution: A PDF function representing the original knowledge available about the process. Priors could also be uninformative showing that there is no initial data available for the system.
- $l(X \mid \theta)$- Likelihood function: The probability of observing the value X given value of θ.
- $f(\theta \mid X)$- Posterior distribution: A PDF function representing the state of knowledge after observing the data.

The term in the denominator of this equation is called the normalizing factor which normalizes the posterior distribution over an area of one and since it is not a function of θ it is considered as a constant; therefore, we can rewrite the Bayesian equation as:

$$f(\theta \mid X) \propto \pi(\theta) l(X \mid \theta)$$

As mentioned previously, the prior function is mostly subjective and describes the initial available knowledge about the system prior to observing data. There are many types of priors which may be selected for use based on the available knowledge and the type of system. Conjugate priors are often used to provide estimated but convenient demonstration of the subjective priors. A conjugate prior has the same function form as the likelihood function which leads to the posterior function being in the same family of distribution as the prior.

4.3. Predictive Model

Predictive model is developed to estimate the number of abnormal events in the next time interval. This model was developed by Meel et al. (2006) using Bayesian theory and joint probability methods. The development of this model is briefly discussed in this section.

Assuming that y_n represents the number of abnormal events occurring in the n^{th} time interval, y_{n+1} would represent the number of abnormal events in the next time interval. This value conditional on the observed data may be obtained by the following approach (Meel et al., 2006).

$$p(y_{N+1}|Data) = \int_0^{\infty} p(y_{N+1}, \lambda|Data)\, d\lambda$$

Where λ is the average number of abnormal events over the time intervals. Using joint probability distribution properties, this equation may be further simplified to:

$$p(y_{N+1}|Data) = \int_0^{\infty} p(y_{N+1}|\lambda, Data)p(\lambda|Data)d\lambda$$

As an example we may consider that the possible number of occurrences of an abnormal event in a time interval of a process follows a Poisson distribution of $(y_n) \propto \lambda^s e^{-N\lambda}$, where s is the cumulative number of abnormal events and N the total number of time intervals, and the prior distribution of λ follows a Gamma distribution of $p(\lambda) \propto \lambda^{\alpha-1}e^{-\beta\lambda}$. Therefore using the predictive model the number of abnormal events occurring within the next time table would be:

$$p(y_{N+1}|Data) = \int_0^{\infty} \frac{\lambda^{y_{n+1}}e^{-\lambda}}{y_{n+1}!} \frac{(\beta+N)^{(\alpha+s)}}{\Gamma(\alpha+s)} \lambda^{\alpha+s-1}e^{-(\beta+N)\lambda}d\lambda$$

$$= \frac{\Gamma(\alpha+s+y_{n+1})}{\Gamma(\alpha+s)\Gamma(y_{N+1}+1)} \left(\frac{\beta+N}{\beta+N+1}\right)^{\alpha+s} \left(\frac{1}{\beta+N+1}\right)^{y_{n+1}}$$

This is a mixture distribution of Poisson-Gamma as it takes a mixture of Poisson distribution, using probabilities from a Gamma distribution as the mixing agents.

Looking closer at the predictive model, it becomes evident that the final equation follows the format of a Negative Binomial distribution. Therefore it may be written as:

$$\binom{\alpha+s+y_{n+1}-1}{\alpha+s-1}\left(\frac{\beta+N}{\beta+N+1}\right)^{\alpha+s}\left(\frac{1}{\beta+N+1}\right)^{y_{n+1}}=\binom{k+r-1}{r-1}p^r(1-p)^k$$

The term on the right hand side is the Negative Binomial distribution where $k = y_{n+1}$, $r = \alpha + s$ and $p = \frac{\beta+N}{\beta+N+1}$. Hence for abnormal events which can be presented by Poisson-Gamma distributions Negative Binomial distribution may be directly used as the predictive model.

4.4. Testing and Validation of the Dynamic Risk Assessment Model

To test and validate the dynamic risk assessment methodology, the approach is applied to a practical case of a pressure water reactor in a nuclear power plant. This plant is a part of the US nuclear regulatory commission's (NRC) accident sequence program. The abnormal event under study in this plant is loss-of-offsite-power which can lead to core damage. The status report issued by NRC for the year 1993 has been used as reference for precursors to potential severe core damage accidents (Johnson and Rasmuson, 1996).

The objective of this study is to determine the core damage frequency and risk associated with the abnormal event of loss of offsite power (LOOP). Figure 4-2 shows the simplified schematics of a PWR.

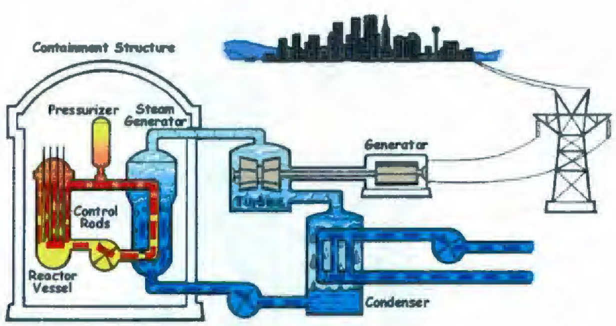

Figure 4-2. Schematics of a pressurized water reactor (PWR) (US NRC, 2007b)

The data available for loss of offsite power events which occurred at the PWR plant in 1993 are shown in Table 4-1. This table represents the events involved in a core damage accident (CD) and their failure probability distributions (Johnson and Rasmuson, 1996).

Event	Description	Distribution	Parameters		M[1]	N[2]
			a	b		
0	Loss of offsite power	Gamma	0.500	0.200	na	2
1	Failure to recover offsite power in 1/2 hour	Beta	0.359	0.838	0	0
2	Reactor trip given a LOOP	None	Constant		2	0
3	Emergency power failure	Beta	0.497	217.302	2	0
4A	Failure of AFW system	Beta	0.500	5059.000	2	0
4B	Failure of auxiliary feedwater (AFW) system given EP failure	Beta	0.475	27.437	2	0
5	PORV is NOT challenged	Beta	10.560	0.440	2	1
6A	PORV does not reseat when challenged	Beta	0.500	1513.152	1	0
6B	PORV does not reseat when challenged given EP failure	Beta	0.455	14.712	0	0
7	Failure to get a seal LOCA	Beta	0.519	0.155	0	0
8A	Failure to recover EP before core uncovery following a seal LOCA	Beta	0.610	0.424	0	0
8B	Failure to recover EP prior to battery depletion	Beta	0.408	6.288	0	0
9A	Failure of high pressure injection (HPI)	Beta	0.500	1982.127	0	0
9B	Failure of HPI with feed and bleed	Beta	0.485	48.015	0	0
10	Failure of high pressure recirculation	Beta	0.498	432.800	0	0
11	PORV fails to open for feed and bleed	None	Constant		0	0
12	Failure of containment spray recirculation	Beta	0.500	5374.344	0	0

Table 4-1. Event distribution information (Johnson and Rasmuson, 1996)

1. M= Number of challenges contained in the data

2. N= Number of failures occurred.

Where PORV is the power operated relief valve and LOCA is loss of coolant accident.

Only two PWR LOOP events occurred in 1993. The operating history for the PWRs was 37.9 reactor years during 1993 (Johnson and Rasmuson, 1996).

With the information above an event tree for the abnormal event of loss of offsite power and with the safety barriers in table 4-1 is developed as shown in Figure 4-3 where CD indicates core damage.

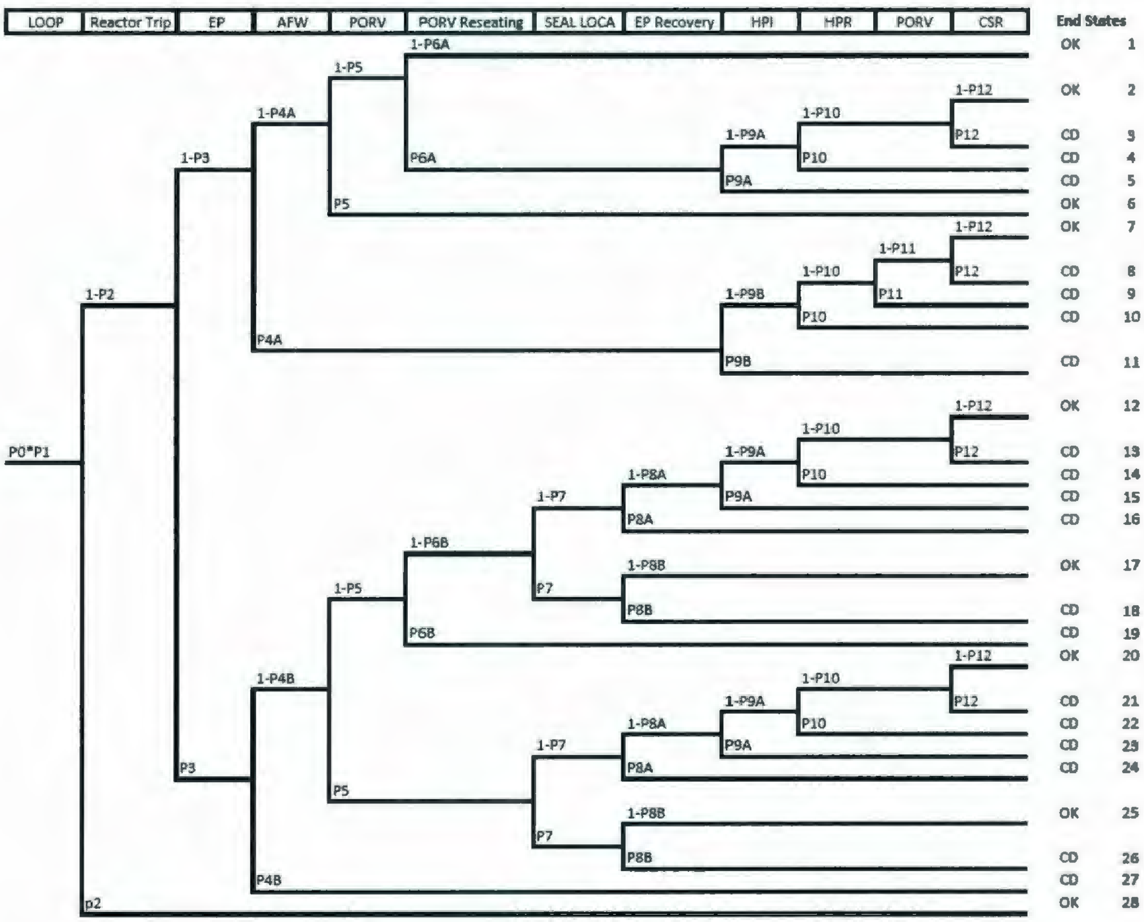

Figure 4-3. LOOP event tree for a PWR plant (revised after Johnson and Rasmuson, (1996))

4.4.1. Posterior Core Damage Frequency:

Using the event tree and the distributions from Table 4-1 the prior end-state probabilities may be easily obtained. In this study, the mean value of each distribution is used for analysis.

After the prior function is developed using the precursor data and Bayesian theory the posterior distribution is obtained. Below is an example of the mathematical formulation for the event 5 ``PORV is not challenged``:

$$Prior\ distribution\ (Beta): f(x) \propto x^{a-1}(1-x)^{b-1} \propto x^{10.56-1}(1-x)^{0.44-1}$$

$$Likelihood\ function\ (Bernoulli): l(Data|x) \propto x^{N}(1-x)^{M} \propto x(1-x)^{2}$$

$$Posterior\ function\ (Beta): f(x|Data) \propto f(x)l(Data|x) \propto x^{a+N-1}(1-x)^{b+M-1}$$

$$f(x|Data) \propto x^{10.56}(1-x)^{1.44}$$

$$Mean_{Prior} = \frac{a}{a+b} = \frac{10.56}{10.56+0.44} = 0.96$$

$$Mean_{Posterior} = \frac{a+N}{a+N+b+M} = \frac{11.56}{11.56+2.44} = 0.826$$

Posterior probabilities of events may be obtained similarly and the end-state probabilities can be calculated using the event tree by multiplying the related event probabilities for a specific end-state. Table 4-2 shows these results as core damage frequencies for both prior and posterior distributions:

End States	End-State Probabilities	
	Prior	Posterior
3-CD	4.E-11	6.E-11
4-CD	5.E-10	7.E-10
5-CD	E-10	2.E-10
8-CD	2.E-10	2.E-10
9-CD	0	0
10-CD	3.E-09	2.E-09
11-CD	3.E-08	2.E-08
13-CD	3.E-11	4.E-11
14-CD	3.E-10	5.E-10
15-CD	6.E-11	E-10
16-CD	6.E-07	6.E-07
18-CD	1.E-07	2.E-07
19-CD	8.E-08	1.E-07
21-CD	6.E-10	3.E-10
22-CD	7.E-09	4.E-09
23-CD	2.E-09	8.E-10
24-CD	9.E-06	5.E-06
26-CD	3.E-06	2.E-06
27-CD	1.E-06	6.E-07

Table 4-2. Prior and posterior core damage probabilities

It is evident that there is considerable difference between prior and posterior core damage frequencies.

Comparing the results from the dynamic risk assessment approach and the study by Johnson and Rasmuson (1996) shows consistency between the failure values. This in turn validates the dynamic risk assessment approach to this point as a learning tool for updating the knowledge concerning system performance. The following section takes a step further in the methodology to develop the updated risk profile of the process.

4.4.2 Consequence Analysis

Following the procedure in section 3.3, after identifying the accident scenario an estimate of the consequences due to core damage, which assuming no radioactive leak to the outside is mostly asset loss, is made. To designate a dollar value for the amount of damage only the asset loss section of the consequence matrix is used which has categorized the loss based on the severity of accident in dollar value. Table 4-3 shows this matrix. Similar matrices may be created for other damages such as human fatality and environmental loss.

Severity Class	Potential asset loss
0	No loss
1	Less than $10,000
2	$10,000-$100,000
3	$100,000-$1,000,000
4	$1,000,000-$10,000,000
5	More than $10,000,000

Table 4-3. Classification of asset loss based on severity

Based on the consequence matrix, all 28 end-states are given a severity class which is shown in table 4-4. It may be seen from this table that although all end-states result in core damage, their severity classes are not the same. This value depends on the units and equipments involved in each path of the event tree.

End State	3	4	5	8	9	10	11	13	14	15	16	18	19	21	22	23	24	26	27
Class	4	4	4	4	4	4	4	5	5	5	5	5	4	5	5	5	5	4	4

Table 4-4. End-state classification based on severity of damage

After each end-state is assigned a dollar value of damage, the associated risk is determined by multiplying the damage value by the related probability. Table 4-5 shows the risk values for the end-states resulting in core damage for prior and posterior probabilities:

End States	Severity Class	Risk Estimation	
		Prior Risk	Posterior Risk
3-CD	4	4.E-04	6.E-04
4-CD	4	5.E-03	7.E-03
5-CD	4	E-03	2.E-03
8-CD	4	3.E-03	2.E-03
9-CD	4	0	0
10-CD	4	3.E-02	2.E-02
11-CD	4	3.E-01	2.E-01
13-CD	5	2.E-03	4.E-03
14-CD	5	3.E-02	5.E-02
15-CD	5	6.E-03	E-02
16-CD	**5**	**4.E+01**	**6.E+01**
18-CD	**5**	**1.E+01**	**2.E+01**
19-CD	4	8.E-01	**1.E+00**
21-CD	5	6.E-02	3.E-02
22-CD	5	7.E-01	4.E-01
23-CD	5	2.E-01	8.E-02
24-CD	**5**	**9.E+02**	**5.E+02**
26-CD	**4**	**3.E+01**	**2.E+01**
27-CD	**4**	**1.E+01**	**6.E+00**

Table 4-5. Risk estimation for end-states resulting in core damage

The cells in bold have a risk value greater than one, which requires prompt attention and risk management efforts. Detailed calculations are presented in Appendix A.

4.4.3. Predictive Model:

Using joint probability method as stated in section 4.3, it is possible to predict the number of abnormal events occurring in the next time interval. The abnormal event in this case study is LOOP and the representative distribution is a Gamma; therefore, with a likelihood function of Poisson distribution the posterior function will be:

$$p(y_n|Data) \propto (\lambda^s e^{-N\lambda})(\lambda^{\alpha-1}e^{-\beta\lambda}) \propto \lambda^{(\alpha+s)-1}e^{-(\beta+N)\lambda}$$

Following the procedure in section 4.3 the Negative Binomial distribution to be used as the predictive model has the following parameters:

$$p = \frac{\beta + N}{B + N + 1}; \; k = y_{n+1}; \; r = \alpha + s$$

Using the above parameters for a Negative Binomial distribution, the number of LOOP events in the next time interval is determined. The Mean of the distribution is selected as the desired value in this study. Table 4-6 shows the results of this predictive model:

Time (years)	**Incident**	**Predictive Model**		
		Probability of success	**Mean**	**Rounded Mean**
1	2	0.545	2.083	**2**

Table 4-6. Predicted number of abnormal events within the next time interval

The testing of this approach has been done by Meel and coworkers for a different case study (Meel and Seider, 2006) using one year of data. The predicted number of incidents in year one is 2, which matches the reported incident. This confirms the applicability and predictability of this approach in conditions where incident data is sparse. However, further testing and validation is required with more data. This model will be a useful tool to forecast the likelihood of accidents and number of likely events in a given period. This in turn would help to revise the risk profile and develop risk management strategies.

This study has tested and validated the abilities of the dynamic risk assessment approach as a learning and predicting tool. The real time risk values obtained by this method for each end state shows the deviation of the risk of the process as it is subjected to abnormal conditions throughout its life cycle. Now that this tool has been validated by an existing study, we may proceed to the next step which is to apply this tool to actual process units.

Chapter 5

APPLICATION OF DYNANIC RISK ASSESSMENT

Application of dynamic risk assessment is demonstrated in this chapter in two case studies related to the process industry. The first cast study is the process facility of an offshore oil and gas platform where the risk of the equipment in use is determined based on the number of occurrence of unwanted events. This case study shows that the application of this tool to such dangerous working conditions may in fact play a critical role in saving valuable human life and assets.

The second case study is based on the incident in Texas City refinery which occurred in March 2005. The objective of this study is to determine whether or not this catastrophic incident was predictable and could have been prevented by this approach. The results and conclusions from each study are presented individually.

5.1. Dynamic Risk Assessment of an Offshore Process facility

5.1.1. Process Description

An offshore oil and gas platform is used to drill wells in the ocean, produce oil and gas, process the fluids and ship the final products to shore. The processing section of an OOG platform generally contains three main parts: wellhead, separators, and gas compressors. Auxiliary equipment such as dehydrators, pumps, etc… are also present but the focus of this work is limited to larger unit operations.

Crude oil enters the separators where it is separated into three major components: oil, gas, and water. Gas condensate may also be separated depending on the size of the platform and composition of the crude. Oil is shipped to onshore process facilities and gas is further processed to high pressure dry gas which is partly used for power generation on the platform, re-injected into the reservoir, and/or transported to onshore facilities.

Dynamic risk assessment is applied on each process unit, due to space limitations the results of three representative units (separator, compressor and flash drum) are discussed.

5.1.2. Separator

5.1.2.1. Posterior Failure Probability

Separators are used to separate crude oil into oil, gas, gas condensate and water, the first separator in the offshore process which is the main focus of this section separates oil and gas. Figure 5-1 shows the cross section of a separator with related control systems.

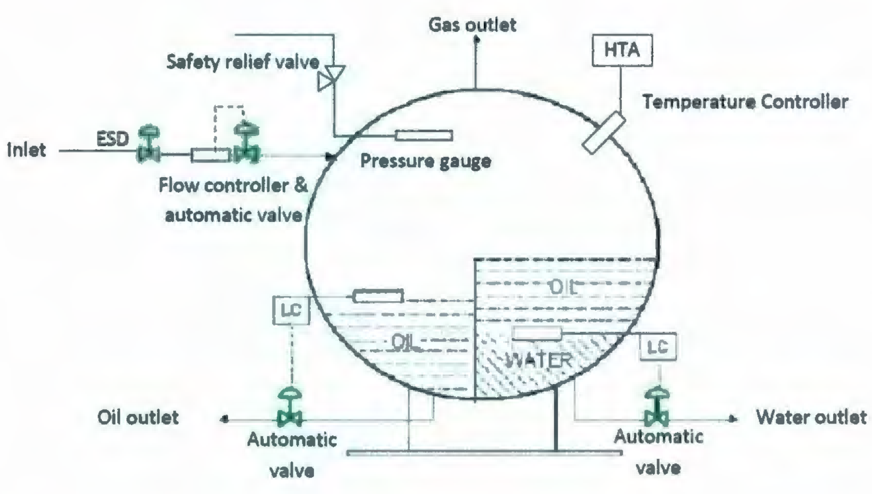

Figure 5-1. Cross section of a spherical separator and control system

Table 5-1 shows the data available after hazard identification of this unit at the design stage. Depending on the sequence of events three possible categories of end-states are possible: a) continued operation, b) process shutdown and c) high pressure release. Release is due to the most credible scenario which is Boiling Liquid Expanding Vapour Explosion (BLEVE) followed by fire. The most credible scenario is defined as the scenario having a combination of both high likelihood of occurrence and scale of damage potential (Khan et al., 2002,a). High pressure development in the separator causes the unit to fail as BLEVE and the vapour cloud on ignition will form a fireball (Khan et al., 2002,b).

Event	Description	Failure frequency			
		Discrete value	Distribution	Distribution parameters	
				a	b
1	Excess flow through the inlet	0.08	Gamma	0.2	0.4
2	Flow controller failure	0.025	Beta	10	390
3	Flow control valve failure	0.02	Beta	9	441
4	Level indicator failure (Oil/Water)	0.02	Beta	11	539
5	Automatic valve failure (Oil/Water)	0.02	Beta	12	588
6	Gas outlet valve chocked or failed	0.07	Beta	20	266
7	Pressure gauge failure	0.02	Beta	10	490
8	Safety relief valve failure	0.0015	Beta	80	53253
9	Temperature controller failure	0.02	Beta	10	490
10	High temperature alarm failure	0.15	Beta	9	51
11	Emergency shutdown system failure	0.2	Beta	2	8

Table 5-1. Failure probabilities of separator components
(Khan et al. 2002,b, plant specific data, safety expert feedback)

Prior probabilities used in the event tree analysis (Figure 5-2) are developed using plant specific data and safety expert's opinion. With the event tree formed, the end-state probabilities are obtained simply by multiplying the probabilities of the associated branches leading to a specific end-state. These results are generally available at the design stage of a process unit.

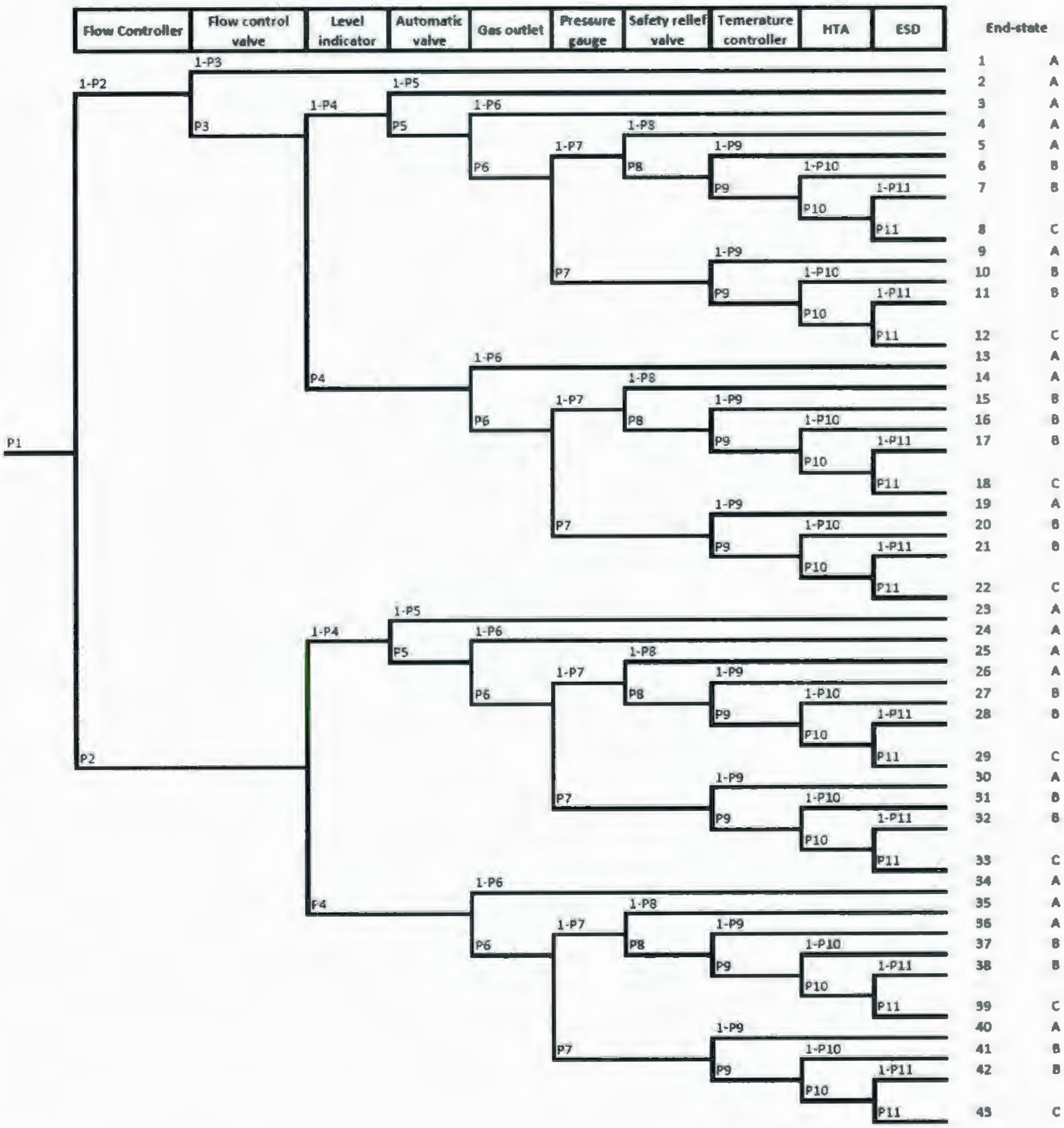

Figure 5-2. Event tree for the abnormal event of excess flow input in a separator

During a five year period after the start of the process the unit is monitored and ASP data during this five years are recorded which are presented in Table 5-2. Using the ASP data the likelihood function is formed and Bayesian theory is applied to calculate posterior probabilities.

	Year 1	Year 2	Year 3	Year 4	Year 5
1-A	4	4	2	4	3
2-A	4	2	3	3	3
3-A	3	1	2	2	2
4-A	2	1	2	1	1
5-A	1	1	2	1	0
6-B	2	2	1	2	1
7-B	1	0	1	1	1
8-C	0	0	0	0	0
9-A	2	2	1	2	1
10-B	1	1	1	0	1
11-B	1	0	1	1	1
12-C	0	0	0	0	0
13-A	4	4	4	2	2
14-A	2	5	5	2	1
15-B	2	2	1	1	1
16-B	1	0	1	1	1
17-B	2	3	1	2	1
18-C	0	0	0	0	0
19-A	1	1	0	1	1
20-B	2	1	1	2	1
21-B	1	1	1	1	1
22-C	0	0	0	0	0
23-A	3	4	4	2	1
24-A	2	0	0	0	2
25-A	2	1	1	1	1
26-A	2	5	2	4	1
27-B	2	2	1	1	1
28-B	1	0	1	1	1
29-C	0	0	0	0	0
30-A	1	0	1	1	1
31-B	2	1	1	2	1
32-B	1	1	1	2	1
33-C	0	0	0	0	0
34-A	4	4	2	4	2
35-A	1	1	2	2	1
36-A	1	1	2	2	1
37-B	3	3	3	1	1
38-B	1	0	1	1	1
39-C	0	0	0	0	0
40-A	2	2	2	2	1
41-B	1	0	1	1	1
42-B	1	2	2	1	1
43-C	0	0	0	0	0

Table 5-2. ASP data from the separator unit during a five year period (Safety expert feedback)

5.1.2.2. Consequence Analysis

With the posterior probability function available, the consequences associated with each category of end-state are determined. According to the severity matrix in Table 3-1 the end-state severity levels with equivalent dollar values for the separator are selected and shown in Table 5-3.

End-state categories	A	B	C
Severity Level	1	2	4
Dollar value	$10,000.00	$100,000.00	$3,000,000.00

Table 5-3. Consequence severity vs. Dollar value for the separator unit

5.1.2.3. Predictive Model

In the last step Bayesian and joint probability theory are used together to develop a predictive model as discussed in Chapter 4 which estimates the number of abnormal events occurring within the next time interval. These values are estimated using the negative binomial approach also discussed in detail in Chapter 4. Table 5-4 shows the results of the predictive model compared to the actual number of initiating abnormal events in each year.

Time (Year)	Data		Mean No. of Event Occurrence
	Incidents	Cumulative Form	
1	0	0	0.143<1
2	0	0	0.083<1
3	0	0	0.059<1
4	1	1	0.273<1
5	1	2	0.407<1

Table 5-4. Predictive model of the separator unit

5.1.3. Compressor

A gas compressor increases the pressure of the gas by reducing its volume. Figure 5-3 shows a gas compressor with its related safety systems.

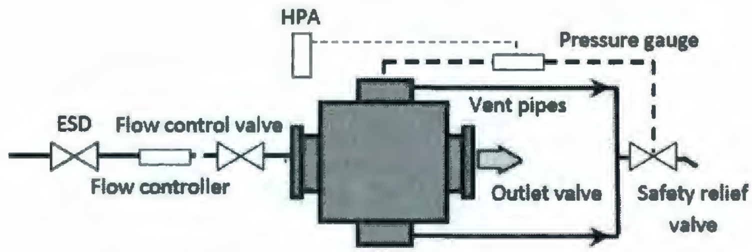

Figure 5-3. Centrifugal gas compressor and safety systems

Hazard identification on this unit leads to the most credible accident scenario being a jet fire. The continuous release of flammable gas from the compressor finding a source of ignition will cause the jet fire (Khan et al., 2002,b). Table 5-5 shows the data available regarding component failure at the design stage of the unit.

Event	Description	Failure frequency			
		Discrete value	Distribution	Distribution parameters	
				a	b
1	Excess flow through the inlet	0.08	Gamma	0.2	0.4
2	Flow controller Failure	0.025	Beta	10	390
3	Flow control valve failure	0.02	Beta	9	441
4	Outlet valve failed closed	0.02	Beta	11	539
5	High pressure gauge failure	0.01	Beta	1	99
6	Vent pipe failure	0.02	Beta	10	490
7	Safety valve failure	0.0015	Beta	80	53253
8	High high pressure alarm failure	0.15	Beta	9	51
9	Emergency shutdown valve failure	0.2	Beta	2	8

Table 5-5 Failure probabilities of compressor components
(Khan et al. (2002,b), plant specific data, safety expert feedback)

Figure 5-4 shows the event tree related to the abnormal event of excess flow entering the compressor. Severity consequences are presented in Table 5-6. Following the same approach as the separator, using the ASP data from 5 years back shown in Table 5-7, the posterior end-state probabilities and risk function are obtained.

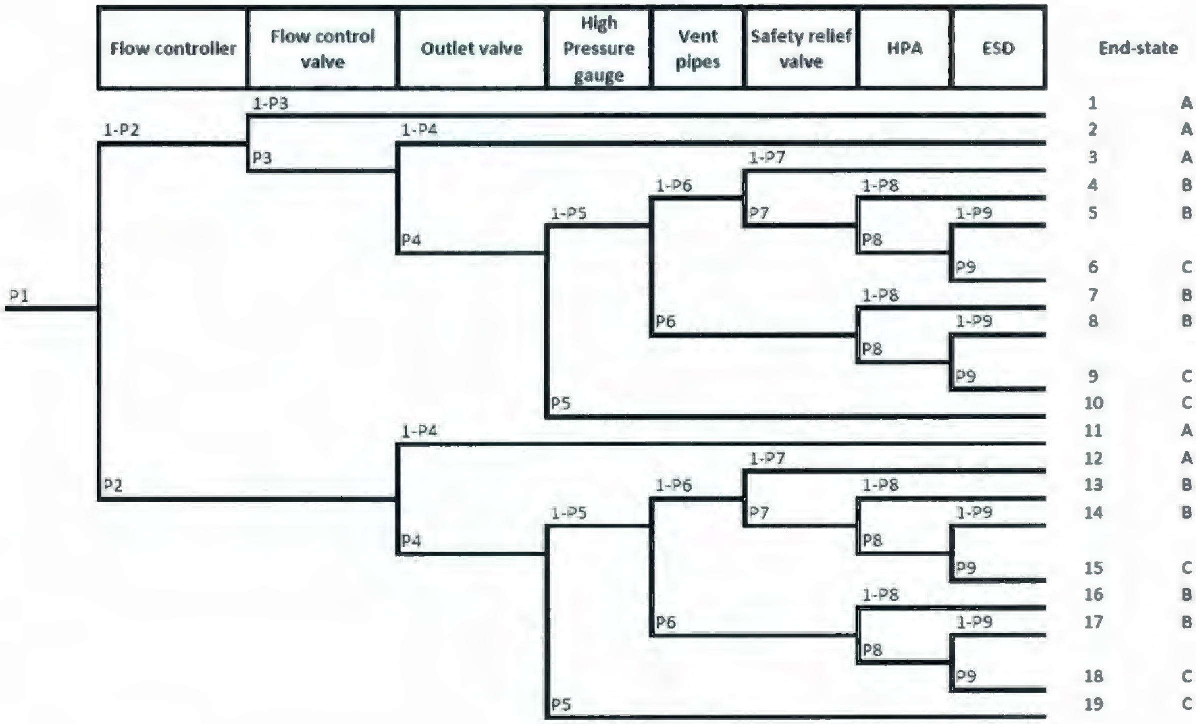

Figure 5-4. Event tree for the abnormal event of excess flow input in a compressor

End-state categories	A	B	C
Severity Level	1	2	3
Dollar Value	$10,000.00	$100,000.00	$1,000,000.00

Table 5-6. Consequence severity vs. Dollar value for the compressor unit

	Year 1	Year 2	Year 3	Year 4	Year 5
1-A	2	2	1	2	1
2-A	2	1	2	1	1
3-A	3	2	1	0	1
4-B	1	0	2	1	0
5-B	1	1	1	1	0
6-C	0	0	0	0	0
7-B	2	2	1	1	0
8-B	1	1	0	1	1
9-C	0	0	0	0	0
10-C	0	0	1	1	0
11-A	2	2	1	1	0
12-A	1	0	1	1	0
13-B	0	2	1	1	0
14-B	1	1	1	1	2
15-C	0	0	1	1	0
16-B	1	1	4	2	0
17-B	2	1	1	0	1
18-C	0	0	0	1	0
19-C	0	0	0	0	0

Table 5-7. ASP data from the Compressor unit during a five year period (Safety expert feedback)

The predictive model for the compressor is also developed with the same approach as the separator which is presented in Table 5-8.

Time (Year)	Data		Mean No. of Event Occurrence
	Incidents	Cumulative Form	
1	0	0	0.143<1
2	1	1	0.500<1
3	2	3	0.941<1
4	2	5	1<1.182<2
5	1	6	1<1.148<2

Table 5-8. Predictive model of the compressor unit

5.1.4. Flash Drum

A flash drum is a vertical vessel used to separate vapour from liquid to facilitate storage of "dry" gas. Figure 5-5 shows the simplified schematics of a flash drum and its related safety systems.

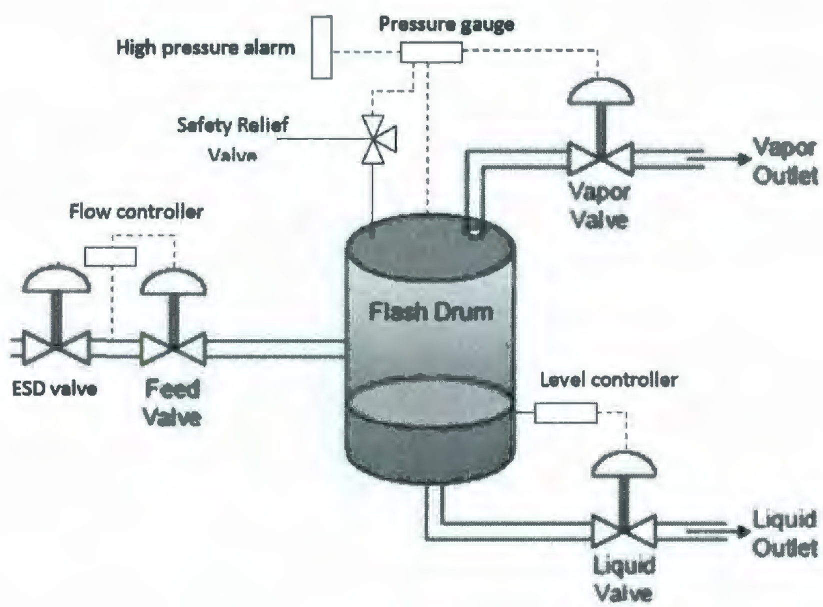

Figure 5-5. Flash drum and safety systems

Applying a hazard identification study for the drum identifies the most credible accident scenario as vapour cloud explosion. Flammable gas released from the flash drum would form a highly flammable vapour cloud which on ignition would burn instantly causing overpressure. Unreleased condensate in the unit would burn as a pool fire (Khan et al., 2002,b).

Table 5-9, 5-10, 5-11 and 5-12 show the failure probability of flash drum components, the consequences in terms of dollar value, the ASP data for 5 years and the predictive model values respectively. Figure 5-6 show the event tree related to the initial abnormal event of excess flow entering the inlet pipe and the prior end-state probabilities.

Event	Description	Failure frequency				
		Discrete value	Distribution	Distribution parameters	
				a	b
1	Excess flow through the inlet	0.08	Gamma	0.2	0.4
2	Flow controller failure	0.025	Beta	10	390
3	Flow control valve failure	0.02	Beta	9	441
4	Liquid level controller failure	0.02	Beta	11	539
5	Level control valve failure	0.02	Beta	1	490
6	Pressure gauge failure	0.02	Beta	8	392
7	Pressure control valve failure	0.02	Beta	9	441
8	Safety relief valve failure	0.0015	Beta	80	53253
9	High pressure alarm failure	0.15	Beta	9	51
10	Emergency shutdown valve failure	0.2	Beta	2	8.

Table 5-9. Failure probabilities of flash drum components
(Khan et al., (2002, b), plant specific data, safety expert feedback)

End-state categories	A	B	C
Severity Level	1	2	3
Dollar Value	$10,000.00	$100,000.00	$1,000,000.00

Table 5-10. Consequence severity vs. Dollar value for the flash drum unit

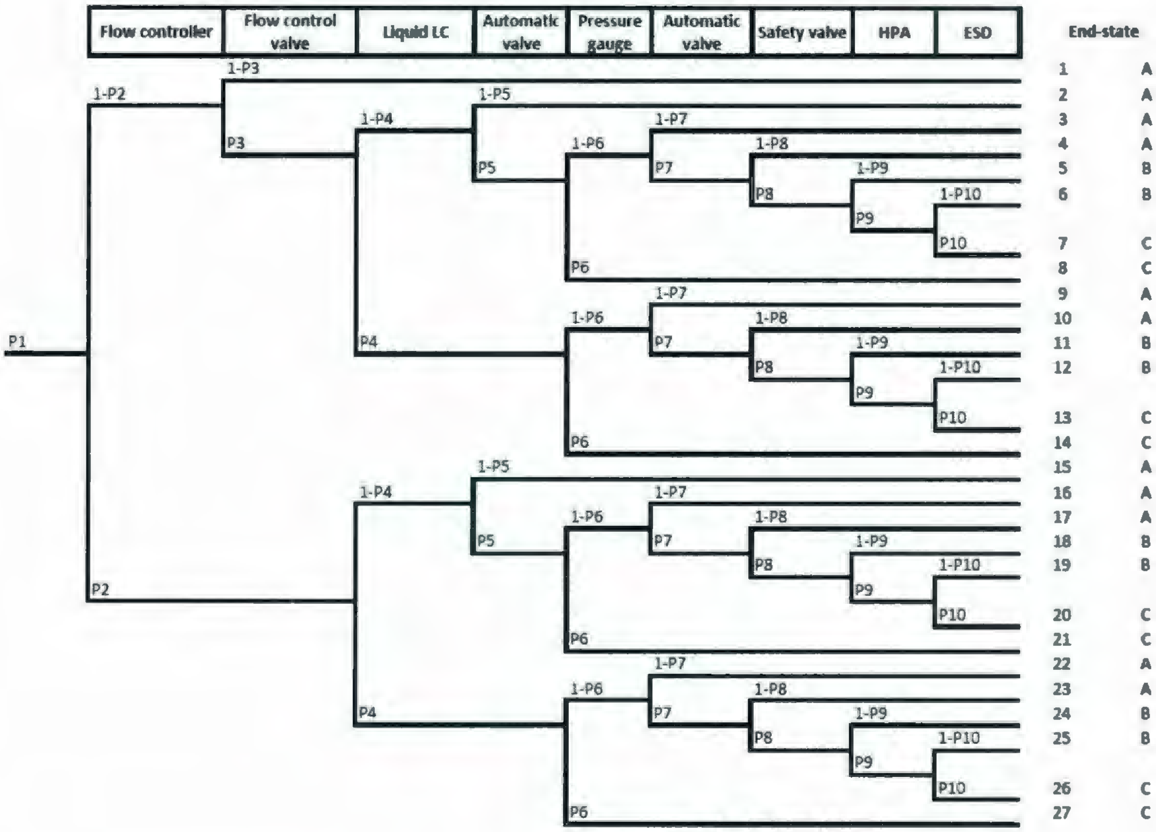

Figure 5-6. Event tree for the abnormal event of excess flow input in a flash drum

	Year 1	Year 2	Year 3	Year 4	Year 5
1-A	5	3	2	4	1
2-A	3	2	2	1	3
3-A	2	2	2	1	1
4-A	5	2	2	4	3
5-B	3	2	2	1	2
6-B	2	2	1	1	2
7-C	0	0	0	0	0
8-C	0	0	0	1	1
9-A	1	2	2	2	1
10-A	4	2	3	1	1
11-B	0	1	2	1	0
12-B	0	1	2	2	1
13-C	0	0	0	0	0
14-C	1	0	0	0	1
15-A	0	1	1	2	1
16-A	4	1	1	3	1
17-A	3	2	1	1	2
18-B	0	1	2	1	1
19-B	0	1	2	2	1
20-C	0	0	0	0	1
21-C	0	0	0	0	0
22-A	0	1	1	2	1
23-A	3	2	2	3	1
24-B	4	1	1	2	1
25-B	1	2	0	1	1
26-C	0	0	0	0	0
27-C	1	0	1	0	1

Table 5-11. ASP data from the Flash drum unit during a five year period

(Safety expert feedback)

Time (Year)	Data		Mean No. of Event Occurrence
	Incidents	Cumulative Form	
1	2	2	1<1.571<2
2	1	3	1<1.333<2
3	1	4	1<1.235<2
4	2	6	1<1.409<2
5	2	8	1<1.519<2

Table 5-12. Predictive model of the flash drum unit

5.1.5. Results and Discussions

5.1.5.1. Individual Units

5.1.5.1.1. Separator

The ASP data of the separator (Table 5-2) shows that even though none of the 280 accident precursor events which occurred in the 5 year period resulted in fluid release, occurrence of other incidents in this period increase the likelihood of this event over the interval. Hence as the posterior results show, the failure probability, and as a result the risk, of the system increases over this time. Table 5-13 and Figure 5-7 show both numerically and graphically the changes in the risk profile over the 5 year period. To show the risk variations more clearly a logarithmic scale is selected for Figure 5-7. It may be observed that the real time risk function is below the risk acceptability limit at the start of unit operation but tends to increase and become significantly greater than this value after the end of the 5 year period.

	Prior Risk	Posterior Risk ($)				
	0	1	2	3	4	5
A	1.00E+04	1.00E+04	1.00E+04	1.00E+04	9.99E+03	9.99E+03
B	9.07E-03	1.23E+00	7.27E+00	2.36E+01	5.61E+01	9.26E+01
C	4.77E-03	7.57E-01	3.93E+00	1.11E+01	2.30E+01	3.45E+01

Table 5-13. Risk profile for the separator unit

It is important to note that between the three possible end-states of continued operation, system shutdown and fluid release causing BLEVE, failure of the system in this study is considered as fluid release.

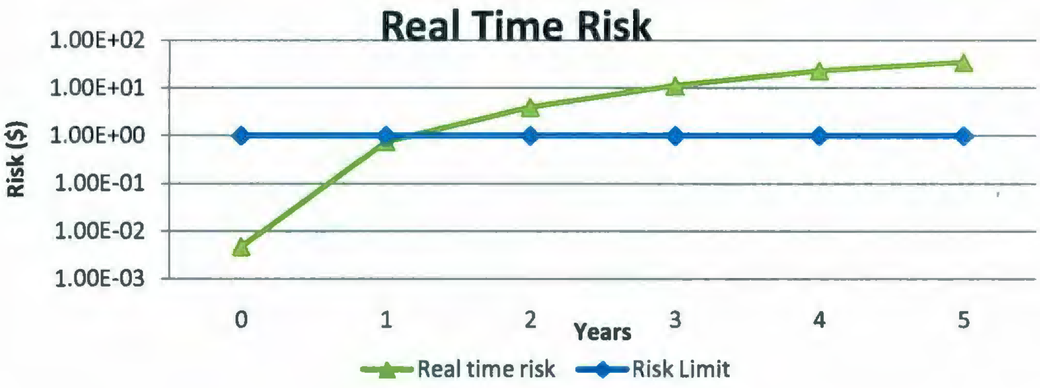

Figure 5-7. Posterior risk profile of the separator unit over 5 years

Regarding the predictive model, as per Table 5-4, it may be concluded that there is a low likelihood of an initiating event occurrence in the fifth year. This may be attributed to the fact that only two initiating events have occurred during this period.

5.1.5.1.2. Compressor

The ASP data of the compressor show that there are indeed incident leading to failure of the system (in this case high pressure fluid release) during the 5 year period. Even though the number of incidents (77) is less than the separator, as Table 5-14 and Figure 5-8 show the risk profile of this unit takes an increasing trend. This trend indicates that the unit starts with a design risk below the risk acceptability limit (1) and increases significantly during the next 5 years.

	Prior Risk	**Posterior Risk ($)**				
	0	**1**	**2**	**3**	**4**	**5**
A	1.00E+04	1.00E+04	1.00E+04	9.99E+03	9.99E+03	9.99E+03
B	1.83E+00	1.06E+01	2.57E+01	5.65E+01	8.99E+01	1.07E+02
C	9.47E-01	3.27E+00	5.77E+00	1.83E+01	3.65E+01	4.01E+01

Table 5-14. Risk profile for the compressor unit

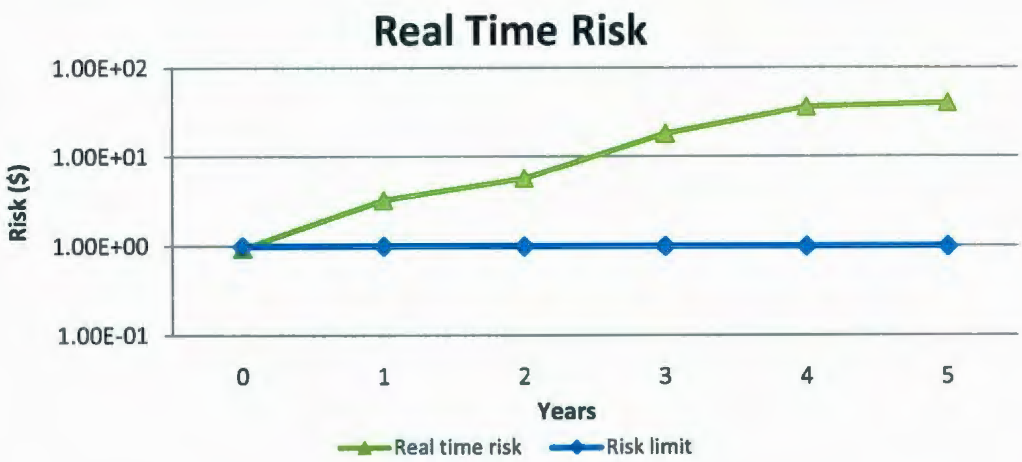

Figure 5-8. Posterior risk profile of the Compressor unit over 5 years

Predictive model for the compressor shown in Table 5-8 also demonstrates that as the rate of initiating event change during the 5 years the model provides new estimates for predicting the number of abnormal events within the next time interval. Even though the changes are not large enough to add one unit to the rounded value (since the number of abnormal events are discrete the values obtained by the model are rounded to omit the decimal digits) variation in the actual mean may be seen.

5.1.5.1.3. Flash Drum

Table 5-15 and Figure 5-9 show the posterior risk profile of the flash drum both numerically and graphically.

The results of the risk analysis follow the same concept of separator and compressor which is increasing with time. The major difference between this unit and the others is that the design risk of this unit is greater than the acceptable risk limit (1) which can be explained by the fact the flash drum is the last unit of the system and is used only as required, hence considering a design risk greater than one is acceptable for this unit.

	Prior Risk	Posterior Risk ($)				
	0	1	2	3	4	5
A	1.00E+04	9.99E+03	1.00E+04	9.99E+03	9.99E+03	9.98E+03
B	5.03E-03	3.81E+01	4.27E-01	1.02E+00	1.97E+00	3.09E+00
C	2.76E+00	4.35E+01	3.51E+01	5.90E+01	8.95E+01	1.35E+02

Table 5-15. Risk profile for the flash drum unit

Figure 5-9. Posterior risk profile of the Flash drum unit over 5 years

Similar conclusions as the compressor can be made for the flash drum regarding the predictive model.

5.1.5.2 Overall Process System

It is not simple to compare the three units of this process together due to the difference in their level of safety and performance. However by reviewing the overall risk of the selected units it may be concluded that all three units show degradation over the 5 year period. This is evident from the increase in the risk profile (Figures 5-7 to 5-9). The risk profile acts as an indicator showing the increasing likelihood of a release occurring within the system. This indicator shows that in the absence of a robust action plan, release and possibly an explosion with great consequences has a reasonable likelihood of occurrence.

As may be seen in Figures 5-7 to 5-9 that the rate of change of the risk profile in early production years is considerably higher than those of the later years (years 3 to 5). This is because of the decreasing trend in the number of incident and/or near misses. In early years defects causing incidents and/near misses were identified and recertified, which has decreased the rate of change of the risk profile,

The trend of the risk profile in Figures 5-7 to 5-9 confirms the common behaviour of a degrading process system without a proper preventive maintenance action plan. Implementing a precise maintenance plan and schedule for each unit which covers both preventive and reactive maintenance would significantly improve the risk profile. Detailed calculation for the three units may be seen in Appendix B.

5.1.6. Conclusion

This study shows that dynamic risk assessment is a useful tool which has the ability to update the risk profile of the system with respect to the ASP data being extracted. This methodology enables the use of a real time risk profile which can alert the management based on the number and type of deviations, incidents, or near misses. This approach not only has the ability to update itself with changes in the system but it is also capable of predicting the number abnormal events in the next time interval. Therefore this tool has the ability to identifying within a process the most vulnerable unit which provides sufficient time to apply accident prevention and risk management.

5.2. Modelling of BP Texas Refinery Accident using Dynamic Risk Assessment Approach

5.2.1. BP Texas City Refinery

5.2.1.1. A Brief History

BP Texas City refinery is located in Texas City, Texas, 30 miles southeast of Houston. With an area of 1,200 acres it contains 29 oil refining units and 4 chemical units and it is able to produce up to 10 million gallons of gasoline per day (about 2.5 percent of the gasoline sold in the United States) as well as jet fuel and chemical feed stock. The number of employees at the time of the accident was reported as 1,800 BP workers and 800 contractors (CSB, 2007).

5.2.1.2. Process Description

The Isomerization unit (ISOM) was installed in the 1980's and consisted of 4 sections: ultrafiner desulfurizer unit, Penex reactor unit, vapor recovery/liquid recycle unit and raffinate splitter unit.

The raffinate splitter where the accident occurred is a distillation tower that takes raffinate, a non-aromatic primary straight chain hydrocarbon mixture and separates it into light and heavy components. Figure 5-10 shows the raffinate section of the ISOM unit.

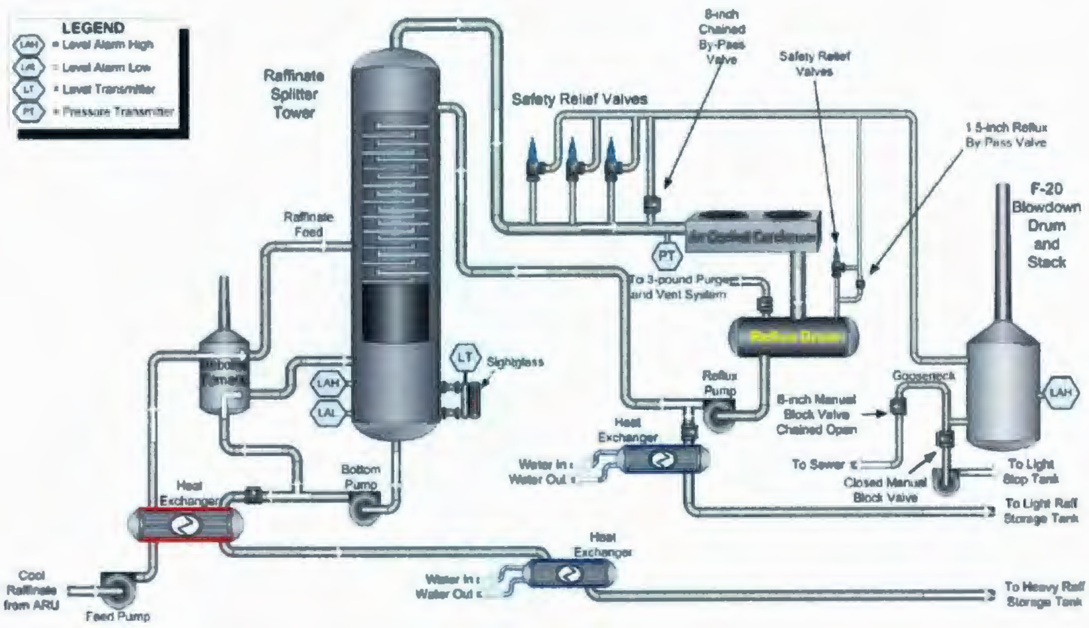

Figure 5-10. Raffinate section of the ISOM unit (CSB, 2007)

The raffinate section of the ISOM unit consists of many components such as reboilers, heat exchangers, air cool condensers, raffinate splitter tower, reflux drum and blowdown drum. In present study we have focused on the three main components of raffinate splitter tower, the reflux drum and the blowdown drum.

5.2.1.3. Raffinate Splitter Tower

The raffinate splitter tower was a 52m vertical distillation tower with a capacity of 586,100 L. Figure 5-10 shows the control systems included in the tower (CSB, 2007):

- Automatic flow control valve: to adjust the feed rate of liquid raffinate.
- Level control Valve: to maintain a constant level in the tower.
- Level transmitter: to display the liquid level in the tower.
- Site glass: to visually indicate liquid level in the tower.

- High and high-high level alarms
- 3 parallel safety relief valves: located in the overhead vapour line and are activated at 40, 41 and 42 Psig respectively.
- Manual chain valve: bypasses the 3 safety relief valves

5.2.1.4. Reflux Drum

The reflux drum operated as a flooded drum and was equipped with the following control systems also displayed in Figure 5-10 (CSB, 2007).

- 1.5 inch reflux bypass valve
- Safety relief valve
- Purge and vent valve

5.2.1.5. Blowdown Drum

The blowdown drum was designed to accept mixed liquid and/or vapor hydrocarbons from venting relief valves during unit upsets or following a unit shutdown. This unit was equipped with the following safety systems which may be seen in Figure 5-10 (CSB, 2007):

- 2 Manual block valves
- High level alarm
- Level site glass

5.2.3. Accident Description

The accident under study occurred on March 23, 2005 at 1:20 PM. The accident occurred during the start up of the ISOM unit killing 15, injuring 180 and resulting in a financial loss of $1.5 billion (CSB, 2007). The detailed report on the accident is published by US Chemical Safety Board that may be accessed through the following link: http://www.chemsafety.gov/index.cfm?folder=completed_investigations&page=info&INV_ID=52 (last checked on April 16, 2009). A simpler brief version is presented below.

The accident occurred during the start-up of the ISOM unit. The raffinate section of the ISOM unit was shut down on Feb21, 2005 and the raffinate splitter tower was drained, gas freed and steamed out. During start up the raffinate tower was overfilled due to faulty readings from the level transmitter. Pressure relief devices opened overfilling the blowdown stack resulting in the release of a flammable liquid geyser from the blowdown drum which was not equipped with a flare. The release of flammables let to an explosion and fire (CSB, 2007).

5.2.4. Dynamic Risk Assessment

As previously discussed in Chapter 4, dynamic risk assessment is applied in 5 steps:

5.2.4.1. Step 1: Scenario Identification

The first step in Dynamic Risk Assessment approach is to identify the potential accident scenario. Accident scenario may be identified by a number of specifications such as the initiating abnormal event, possible end-states and safety barriers or protective layers involved. It is important in each scenario to clarify the definition of failure as without this definition the methodology has no application.

As the accident in BP Texas City refinery has already occurred scenario identification was accomplished by reviewing the reports issued on the accident. According to the final report issued by CSB in 2007, the initial abnormal event is excess flow of liquid raffinate entering the splitter tower. Three possible end-states which may occur from this initiating event are process upsets (A), process shutdowns (B) and fluid release (C). Failure in this scenario is defined as fluid release (C) which on finding a source of ignition may lead to an explosion with severe consequences. The accident in BP Texas city was caused by a chain of events leading to an end-state of category (C).

Table 5-16 shows the failure probabilities of safety barriers of the ISOM unit involved in this scenario in terms of discrete values and distributions:

#	Event Description	Failure frequency			
		Discrete value	Distribution	Distribution parameters	
				a	b
1	Excess feed loading	0.08	Gamma	0.2	0.4
Raffinate splitter tower control system:					
2	Failure of level transmitter	0.01	Beta	11	1089
3	Failure of high level alarm	0.15	Beta	9	51
4	Failure of level site glass	0.1	Beta	10	90
5	Failure of high high level alarm	0.15	Beta	9	51
6	Failure of heavy raffinate level control valve	0.02	Beta	10	490
7	Failure of manual chain valve bypassing the three relief valves	0.2	Beta	2	8
8	Failure of first automatic safety valve (set at 40 psig)	0.015	Beta	80	5253
9	Failure of second automatic safety valve (set at 41 psig)	0.015	Beta	80	5253
10	Failure of third automatic safety valve (set at 42 psig)	0.015	Beta	80	5253
Reflux drum					
11	Failure of 1.5 inch reflux bypass valve	0.02	Beta	9	441
12	Failure of safety relief valve	0.015	Beta	80	5253
13	Failure of vent and purge valve	0.02	Beta	10	490
Blowdown drum					
14	Failure of 6 inch manual block valve chained open	0.2	Beta	3	12
15	Failure of high level alarm	0.15	Beta	9	51
16	Failure of level site glass	0.1	Beta	10	90
17	Failure of Manual block valve kept closed	0.2	Beta	2	8
18	Failure of ESD valve	0.2	Beta	2	8

Table 5-16. Failure probabilities of the ISOM unit safety barriers
(Source: Plant specific data, safety expert feedback)

5.2.4.2. Step 2: Prior Function Calculation

With all safety barriers and failure frequencies known the next step is to form the event tree for this scenario. Figure 5-11 shows part of the event tree for the ISOM unit. The complete event tree may be seen in Appendix C. From the event tree it is evident that a total of 190 possible end-states exist for this scenario which fall into any of the three categories of A, B and C as previously discussed.

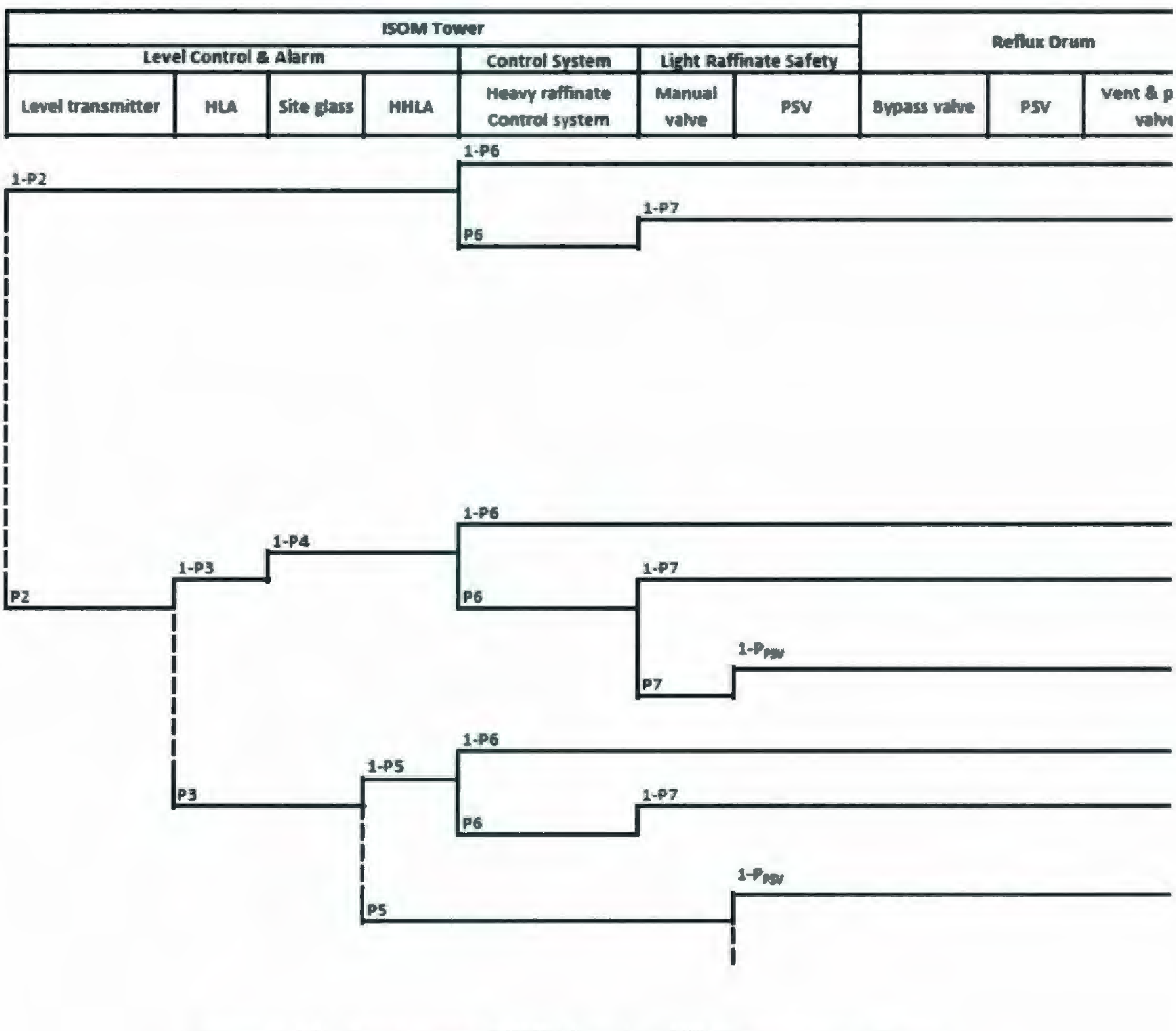

Figure 5-11. Event tree of ISOM unit in BP Texas city refinery

The prior failure function of each safety system represents our knowledge about the system prior to the start of operation. If no knowledge is available an uninformative prior may be used. Herein, as shown in Table 5-16, the prior failure probabilities of each safety system is presented both as a discrete value and a probability density function of type Beta. Beta is generally selected to represent the failure probability of a system as this distribution is used to describe uncertainty about the occurrence of an event, given a number of trials "*n*" have been made with a number of recorded successes "*s*" (Vose, 2003). Parameters of these distributions are selected such that the mean values would match the discrete failure probabilities. Any prior end-state probability may be calculated by multiplying the failure probabilities of the relative safety barriers of each branch connecting the initial event to that particular end-state.

5.2.4.3. Step 3: Formation of the likelihood function

Up to this point dynamic risk assessment has followed the same procedure as a conventional quantitative risk assessment approach. However as discussed in Chapter 4, the novelty of this methodology begins with the formation of the likelihood function. This function is formed using real time data from the process as it operates which represent the number of near misses and incident which occur within the process during the period of study.

In the BP Texas City case study ASP data are collected from the CBS 2007 report which has data records since 1994. These events have been divided into the two categories of process shutdown (B) and release (C). Table 5-17 shows category C of these events.

Many approaches exist for selecting likelihood functions, among the most convenient is using a conjugate pair of the prior function. Beta and binomial distributions are conjugate pairs and hence binomial distribution is selected to represent the likelihood function. This choice is convenient due to the fact that ASP data are specific numbers within a discrete domain which is also best presented by a binomial distribution. Therefore the likelihood function may be defined as:

$$f(Data|x) = \binom{n}{s} x^s (1-x)^f$$

Where $f(Data|x)$ denotes the likelihood function, n is the total number of trials, s is the number of successes and f is the number of failures which can also be shown as n-s.

Date	Description	End-state
12-Feb-94	115ft tall DIH tower filled with liquid, which lead to emergency relief valves opening to the ISOM blowdown system. A large amount of vapour was seen coming from the blowdown drum; high flammable vapour readings were measured at ground level in the area. The ISOM unit was shut down.	Release
17-Feb-94	Leaking DIH relief valves caused a similar accident as above that resulted in a vapour release out of the blowdown stack. A section of ISOM unit was shut down.	Release
27-Feb-94	The ISOM stabilizer tower emergency relief valves opened 5 or 6 times over 4 hours. A large vapour cloud was observed near ground level.	Release
08-May-95	An 8" chain vent valve off the raffinate splitter tower overhead piping was inadvertently left open for over 20 hours during a raffinate section start up resulting in a significant flammable vapour release out of the blowdown stack. Hydrocarbon vapours were reported as "pouring out" of the blowdown drum in the ISOM logbook and high flammable vapour readings were measured at ground level. The valve was eventually closed.	Release
04-Oct-98	Blowdown stack caught fire during stormy weather.	Fire
16-Jan-99	During partial ISOM unit shutdown that required draining liquid from process equipment into the blowdown system, the draining resulted in liquid flowing into the sewer system by way of the piping that was chained open off the drum to the sewer. The high level alarm on the blowdown drum below the outlet of the piping to the sewer should have been triggered by the rising high liquid level but was not. Underground sewer boxes designed to hold and separate out liquid hydrocarbons filled and released flammable vapours from the box seals.	Release
23-Jul-00	Fuelled by leaking pressure relief valves on the hydrogen steam drier the ISOM blowdown stack caught fire and continued to burn over five 12 hour shifts.	Fire
25-Mar-04	The DIH tower Pressure relief valves again lifted after a short loss of electric power to the ISOM unit resulting in a significant vapour cloud at or near ground level.	Release

Table 5-17. ASP data of category C in BP Texas city refinery (CSB 2007)

5.2.4.4. Step 4: Posterior Function Calculation

Posterior failure function may be obtained from the prior and likelihood functions using Bayesian inference. The posterior function can be formulated as shown below:

$$f(x|Data) \propto f(Data|x)f(x)$$

Where $f(x|Data)$ is the posterior function, $f(Data|x)$ is the likelihood function and $f(x)$ is the prior. Therefore, for the ISOM unit of the BP Texas City refinery the posterior failure function may be shown as:

$$f(x|Data) \propto x^{a-1}(1-x)^{b-1}x^{s}(1-x)^{f} \propto x^{a+s-1}(1-x)^{b+f-1}$$

It may be noted that the posterior function is the same distribution type as the prior (Beta) with the parameters updated by the likelihood function. The mean value of the posterior function which represents the failure probability of a protective layer in the event tree is updated from the prior mean of $\frac{a}{a+b}$ to $\frac{a+s}{a+s+b+f}$.

Posterior end-state probabilities may be obtained using the event tree approach.

5.2.4.5. Step 5: Consequence Assessment

To this point the previous sections demonstrate the probability assessment of the methodology. To develop the risk profile consequence assessment is also required.

Consequence assessment is a straight forward approach as the consequence of an abnormal event is considered to remain constant throughout the lifetime of the process.

In the BP case study the focus of consequence assessment is on asset loss and human fatality, the two categories in which the consequences were severe. Each group of end-states is matched with a severity class. The classifications and equivalent dollar value of damage are shown in Table 5-18.

With all posterior probabilities and their related consequences known, posterior risk is obtained by multiplying the posterior failure probability of each end-state by its related consequence. The posterior risk profile may be developed over the period of study (1994-2005) as a function of time.

End-State Category	Severity Class	Dollar value of damage
A	1	$10,000.00
B	2	$100,000.00
C	4	$10,000,000.00

Table 5-18. Classification of end-states in BP Texas city case study

5.2.5. Results and Discussion

The BP Texas City refinery has been analyzed using dynamic risk assessment methodology for a period of 11 years (1994-2005) as a mean to test and validate this approach as a predictive tool for accident occurrence. Abnormal events causing process upsets, shutdown and release were considered in this study for the development of the posterior risk profile. It is important to note that risk in present study is defined for "failure" which is considered as release. Although other end-states may affect the risk, they are not considered as part of the risk profile. Furthermore, the analysis is conducted using publically available information of the BP Texas City refinery incident, which is sufficient to make scientifically valid conclusive observations. However, there may be confidential data that may refine or revise the risk profile which the authors do not have access to. For example, data on the number of process upsets were not available throughout the 11 years and therefore were not used in this study. Table 5-19 illustrates the results of the dynamic risk assessment over the period of 11 years.

Years	Risk ($)	
	B	C
0	1.04E+02	2.59E+03
1	2.40E+02	1.33E+04
2	4.35E+02	2.37E+04
3	5.45E+02	2.72E+04
4	7.52E+02	3.22E+04
5	9.11E+02	4.25E+04
6	1.21E+03	5.70E+04
7	1.43E+03	6.79E+04
8	1.72E+03	7.38E+04
9	2.02E+03	7.91E+04
10	2.30E+03	8.29E+04
11	2.61E+03	9.66E+04

Table 5-19. Risk values of the ISOM unit from 1994-2005

Table 5-19 shows the risk associated with release is greater than process shutdown even at the beginning of the study (1994) and risk profiles (both unplanned shutdowns and release) increase by approximately one order of magnitude by the end of the 11 years (2005). Figure 5-12 shows the risk profile graphically as a function of time.

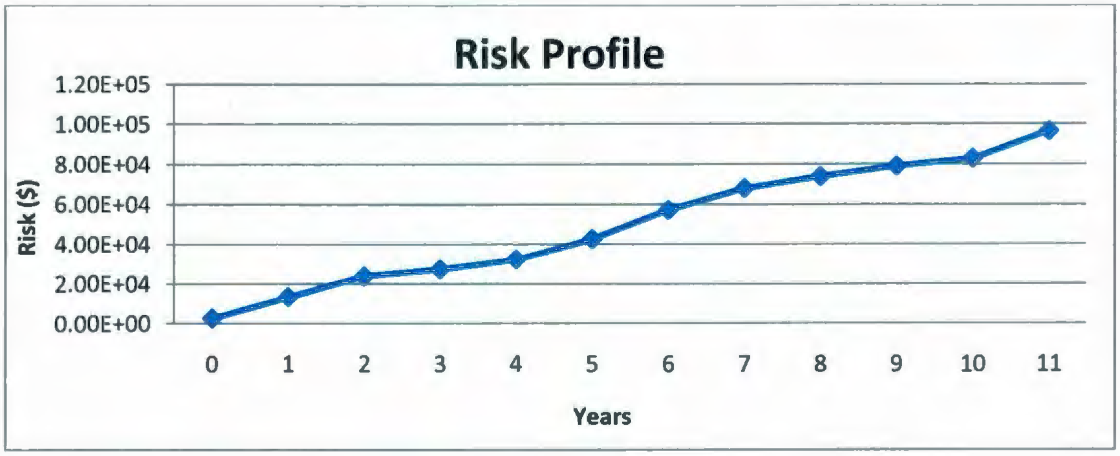

Figure 5-12. Risk profile of the ISOM unit

The risk profile in Figure 5-12 is an indicator of the increasing risk of a release occurring within the system. This indicator shows that in the absence of a robust action plan, an accident of major consequences has a reasonable likelihood of occurrence. The increasing trend of the risk profile represents the common behavior of a degrading process system without a proper preventive or predictive maintenance plan. Implementing a precise maintenance plan for each unit which covers both preventive and reactive maintenance would significantly improve the risk profile. It is important to note that although the risk profile shown herein is developed without the ASP data of category A (process upsets) it still shows a significant increase over the 11 years. With data from safety audits and recorded near misses and incidents, the actual risk profile would likely show a more dramatic increasing trend for the same duration.

Dynamic risk assessment is an important learning tool but is can also be used as a predictive tool to estimate accident likelihood within the next time interval. Figure 5-13 shows the failure frequency of the ISOM unit.

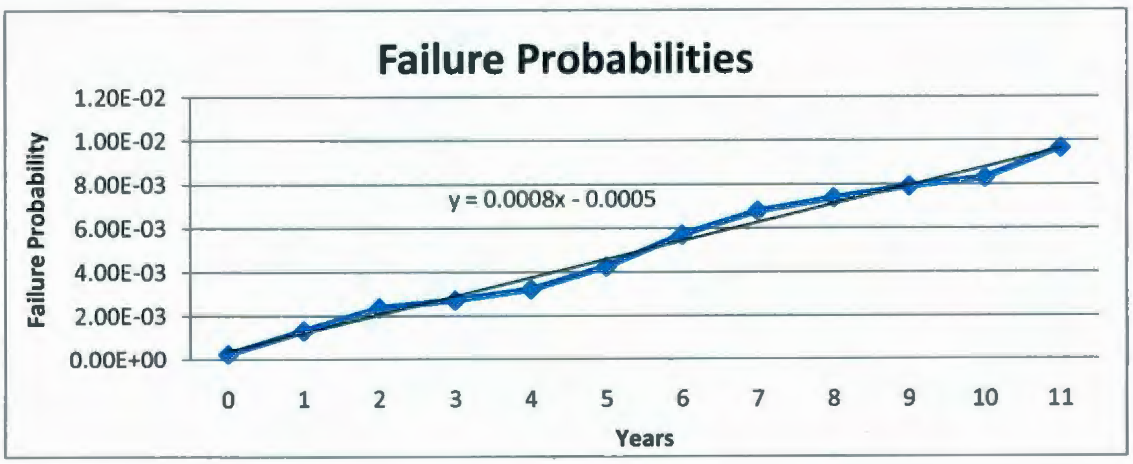

Figure 5-13. Failure frequency of the ISOM unit

The slope of the trendline shown in Figure 5-13 represents the hazard rate, which is the probability of failure per unit time associated with the raffinate tower. This above equation could be used as a predictive tool to estimate the average occurrence probability of a release within the different time intervals. As an example, the average probability of release in the 12 years may be obtained simply by substituting the value in the equation:

$$p(t = 12) = 0.0008 \times 12 - 0.0005 = 0.0091$$

The above approach is very straight forward and easy to use, however there are disadvantages. According to the above equation failures are equally distributed over the time domain even though in reality the occurrence of failure over time is random. Also, with this equation it is only possible to calculate the average probability of one release over the next time period with the assumption that the system is behaving as good as it was before. To overcome this problem Poisson process may be used. Over longer periods of the time, for low likelihood events both results would converge.

A Poisson process is a simple model of a stochastic point process. A stochastic point process is characterized by events occurring at instants distributed randomly over the time domain. Thus this model accounts for the randomness of release in a process. In a Poisson process the probability distribution of the number of failures in a time interval is (Ebeling, 2000):

$$\Pr(N_t = j) = \frac{(\lambda t)^j \, e^{-\lambda t}}{j!}$$

Where j is number of releases in a time interval and λ is the hazard rate. Therefore, according to the hazard rate model obtained from the dynamic risk assessment approach probability of j events occurring in t years will be:

$$\Pr(N_t = j) = \frac{(0.0008t)^j \, e^{-(0.0008t)}}{j!}$$

To validate the model recorded data of the number of releases through the 11 years are used to calculate the probability of release in each time interval using both the linear approach and the Poisson process. The probability of a release in year 12 is calculated to demonstrate the predictive abilities of the model. Table 5-20 shows the results:

Years	Probability of release by Linear Hazard Model		Probability of release Poisson Process	
	Discrete	Cumulative	Discrete	Cumulative
1	3.00E-04	3.00E-04	8.00E-04	8.00E-04
1	3.00E-04	6.00E-04	8.00E-04	1.60E-03
1	3.00E-04	9.00E-04	8.00E-04	2.40E-03
2	1.10E-03	2.00E-03	1.60E-03	4.00E-03
5	3.50E-03	5.50E-03	3.99E-03	7.99E-03
6	4.30E-03	9.80E-03	4.79E-03	1.28E-02
7	5.10E-03	1.49E-02	5.58E-03	1.84E-02
11	8.30E-03	2.32E-02	8.76E-03	2.71E-02
12	9.10E-03	3.23E-02	9.55E-03	3.67E-02

Table 5-20. Occurrence probability of release in the ISOM unit
(The last row is predictive results)

As Table 5-20 indicates the likelihood of release occurrence increases significantly with time. In the early stage there were significant difference in the release probabilities between the linear hazard model and the Poisson process based likelihood estimate. The linear hazard rate model gives a lower likelihood of release. However over longer periods (predictive year; shown by dark background) both models converges and give just above 3% chances of a release occurrence. This is a fairly high value by all standards. In fact from a process facility perspective, a release would be considered eminent. In a standard process facility, safety systems are designed to keep the release probability as low as one in ten thousand to one in hundred thousand.

5.2.6. Conclusion

This study demonstrates the testing and application of the dynamic risk assessment method developed in earlier studies as a powerful learning tool with predictive abilities. This tool is heavily dependent on the incident and near miss data, the preciseness of the data dictate the accuracy of the approach and demonstrate the importance of a strong safety culture throughout the process facility and also monitoring and recording of the incident. Applicability of this tool to the BP case study shows that the accident was predictable and may have been prevented if dynamic risk assessment was applied to the process unit and a robust action plan was developed to resolve the issues.

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1. Summary

This study has demonstrated the importance of the dynamic risk assessment approach in the process industries. After an overview of the concepts of QRA this work begins by a detailed description of the dynamic risk assessment approach using accident precursor data and Bayesian theory. The approach is then tested and validated by a study previously conducted on a pressurized water reactor as part of the U.S. regulatory commission. After validating the dynamic risk assessment model, the approach is applied to two case studies in order to demonstrate its ability as an updating and predictive tool in process facilities.

The first study was on the process facility of an offshore oil and gas platform. This tool established convincing results by determining the risk profile of each unit in the time frame and therefore identifying the most critical unit of the process using the accident precursor data. Also, the predictive abilities of the model were demonstrated by calculating the number of abnormal events in the next time interval.

The second study was based on the BP Texas City accident in 2005. Using the ASP data from the reports issued on the event, the risk profile of the process unit was obtained and revised throughout its lifetime. The results of this study was also encouraging as it demonstrated that the accident was predictable and may have been prevented if the dynamic risk assessment model was applied to the process in time.

The case studies show great potential in the dynamic risk assessment approach as a predictive tool to be incorporated in quantitative risk assessment and management in the near future.

6.2. Conclusion

This study shows that the dynamic risk assessment approach is a powerful tool with updating and predicting abilities which can be applied successfully to the process industry. The methodology may be used as part of a QRA approach to develop the real time risk profile of a process based on the number and type of deviations, incidents, or near misses. Therefore, it is clear that the tool is heavily dependent on the ASP data, in other words, the preciseness of the data dictates the accuracy of the approach. This emphasises more on the importance of a strong safety culture throughout the process facility to monitor and record all abnormal events experience by the process including process upsets, near misses and incidents. With a strong safety culture in place, the application of this tool assures the availability of the real time risk profile of the process. Using the real time risk profile along with a predictive model would help in rectifying issues early on before they escalate to accident. These abilities make this tool very valuable for risk management and decision makers.

6.3. Future Work

It is important to note that this study does not cover the following aspects:

- Data dependencies
- Expertise required to model and interpret results
- The need for precise process system model (prior information)

- Modelling uncertainties
- Parameter reliability

This work may be improves through:

- Non-conjugate prior-posterior distributions: so far in this work to avoid complexity in calculations, all prior-posterior distributions are selected as conjugate pairs. Hence it is required to investigate other types of prior distributions and their effects on the posterior function.
- Empirical distributions
- Linking event and fault trees for integrated dynamic risk simulation.

Details on the specific aspects of the recommended work scopes such as accident precursor data in terms of discrete event happening over intervals of time, initiating event frequency, and past failure behaviour of safety barriers will also be required.

Chapter 7

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APPENDIX A

Risk assessment of a pressurized water reactor (PWR) plant

Events	Event Priors		Event Posteriors	
	Original Data	Mean Values	Original Data	Mean Values
P0	1.00E-01	1.00E-01	5.83E-02	5.83E-02
P1	3.00E-01	3.00E-01	3.00E-01	3.00E-01
P2	1.00E+00	1.00E+00	1.00E+00	1.00E+00
P3	2.28E-03	2.28E-03	2.26E-03	2.26E-03
P4A	9.88E-05	9.88E-05	9.88E-05	9.88E-05
P4B	1.70E-02	1.70E-02	1.59E-02	1.59E-02
P5	9.60E-01	9.60E-01	8.89E-01	8.26E-01
P6A	3.30E-04	3.30E-04	3.30E-04	3.30E-04
P6B	3.00E-02	3.00E-02	2.81E-02	3.00E-02
P7	7.70E-01	7.70E-01	7.70E-01	7.70E-01
P8A	5.90E-01	5.90E-01	5.90E-01	5.90E-01
P8B	6.09E-02	6.09E-02	6.09E-02	6.09E-02
P9A	2.52E-04	2.52E-04	2.52E-04	2.52E-04
P9B	1.00E-02	1.00E-02	1.00E-02	1.00E-02
P10	1.15E-03	1.15E-03	1.15E-03	1.15E-03
P11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
P12	9.30E-05	9.30E-05	9.30E-05	9.30E-05

Table A-1. Single event probabilities, dynamic risk assessment approach vs. the original data

End States	Prior End-state probabilities		Posterior End-state probabilities	
	Original Data	Mean values	Original data	Mean values
3-CD	3.7E-11	3.67E-11	5.9E-11	5.92E-11
4-CD	4.5E-10	4.54E-10	7.3E-10	7.33E-10
5-CD	1.0E-10	9.97E-11	1.6E-10	1.61E-10
8-CD	2.7E-10	2.72E-10	1.6E-10	1.58E-10
9-CD	0.0E+00	0.00E+00	0.0E+00	0.00E+00
10-CD	3.4E-09	3.36E-09	2.0E-09	1.96E-09
11-CD	3.0E-08	2.96E-08	1.7E-08	1.72E-08
13-CD	2.3E-11	2.29E-11	7.1E-11	3.66E-11
14-CD	2.8E-10	2.83E-10	8.8E-10	4.53E-10
15-CD	6.2E-11	6.21E-11	1.9E-10	9.94E-11
16-CD	3.5E-07	3.54E-07	5.6E-09	5.67E-07
18-CD	1.2E-07	1.22E-07	2.0E-07	1.96E-07
19-CD	8.1E-08	8.07E-08	1.2E-07	1.29E-07
21-CD	5.7E-10	5.66E-10	5.8E-10	3.03E-10
22-CD	7.0E-09	7.00E-09	7.3E-09	3.75E-09
23-CD	1.5E-09	1.54E-09	1.6E-09	8.22E-10
24-CD	8.8E-06	8.76E-06	1.6E-06	4.69E-06
26-CD	3.0E-06	3.03E-06	1.6E-06	1.62E-06
27-CD	1.2E-06	1.16E-06	6.3E-07	6.28E-07

Table A-2. End-state probabilities, dynamic risk assessment approach vs. the original data

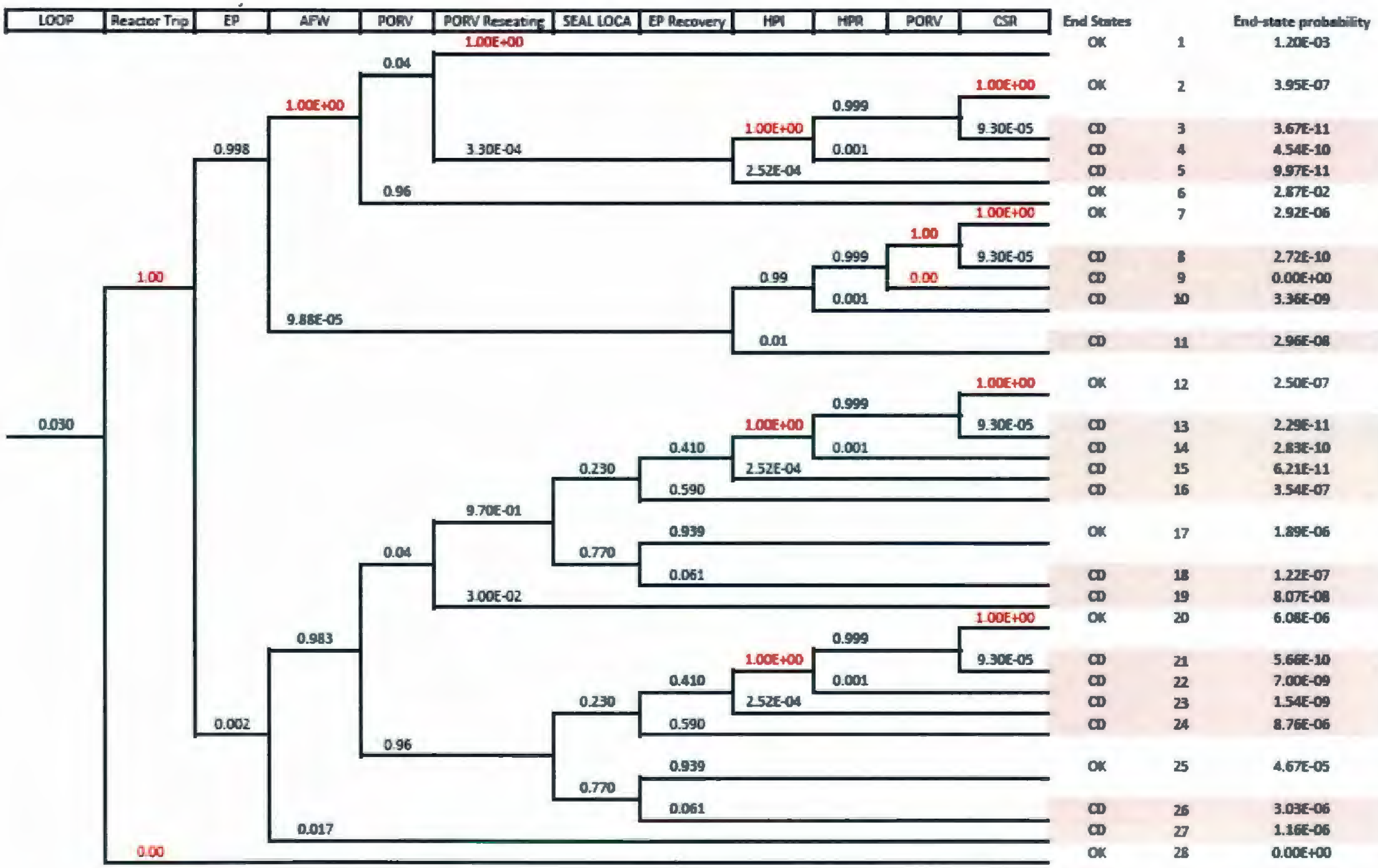


Figure A-1. Prior end-state probability calculation using event tree

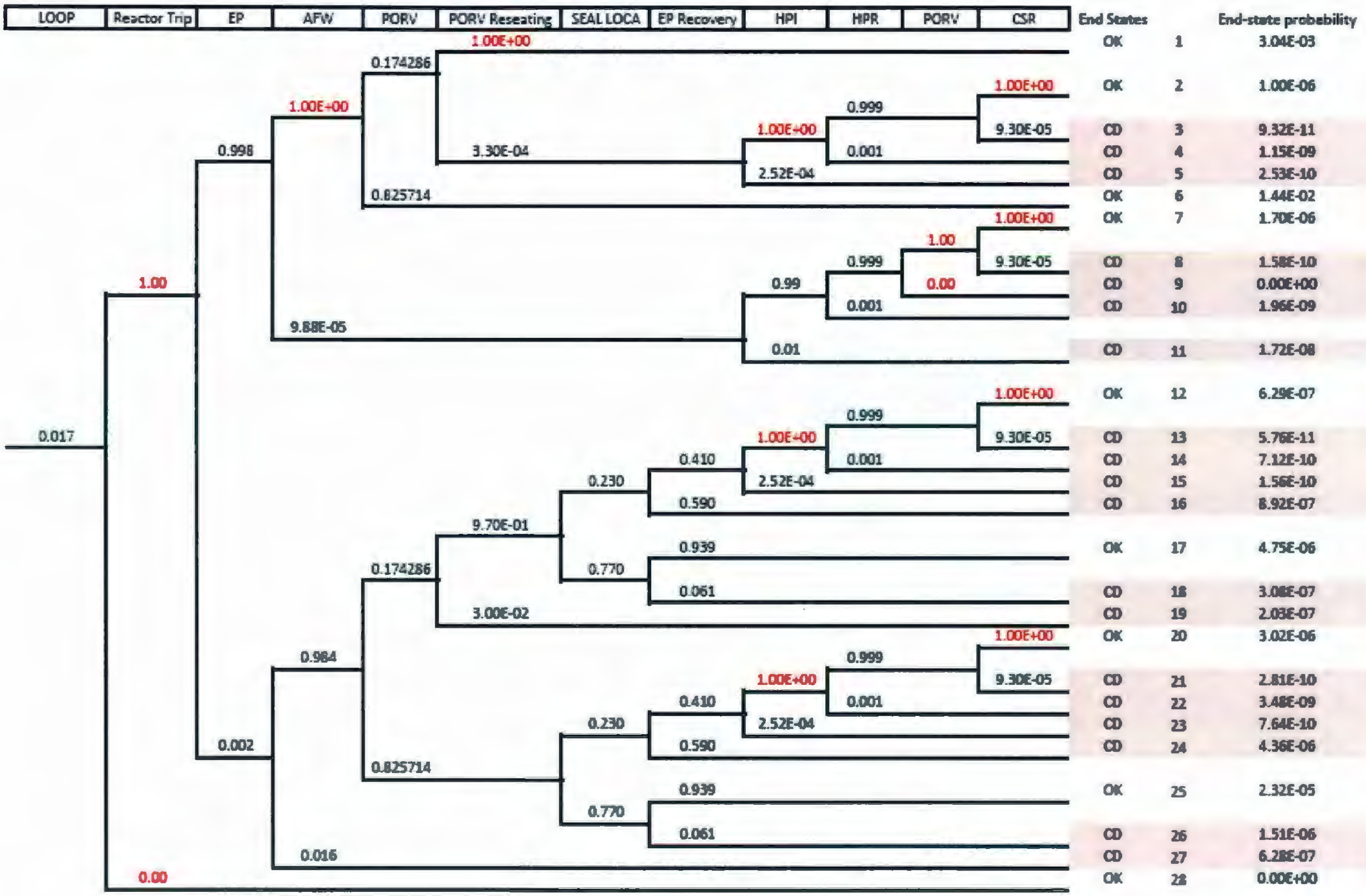


Figure A-2. Posterior end-state probability calculation using event tree

End-State	Severity level
1	0
2	0
3	4
4	4
5	4
6	0
7	0
8	4
9	4
10	4
11	4
12	0
13	5
14	5
15	5
16	5
17	0
18	5
19	4
20	0
21	5
22	5
23	5
24	5
25	0
26	4
27	4
28	0

Table A-3. Consequence severity table

End States	Severity Class	Prior Risk Estimation		Posterior Risk Estimation	
		Original Data	Mean values	Original data	Mean values
3-CD	4	3.70E-04	3.67E-04	5.90E-04	5.92E-04
4-CD	4	4.50E-03	4.54E-03	7.30E-03	7.33E-03
5-CD	4	9.97E-04	9.97E-04	1.60E-03	1.61E-03
8-CD	4	2.72E-03	2.72E-03	1.60E-03	1.58E-03
9-CD	4	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10-CD	4	3.36E-02	3.36E-02	2.00E-02	1.96E-02
11-CD	4	2.96E-01	2.96E-01	1.70E-01	1.72E-01
13-CD	5	2.29E-03	2.29E-03	7.10E-03	3.66E-03
14-CD	5	2.83E-02	2.83E-02	8.80E-02	4.53E-02
15-CD	5	6.21E-03	6.21E-03	1.90E-02	9.94E-03
16-CD	5	**3.54E+01**	**3.54E+01**	5.60E-01	**5.67E+01**
18-CD	5	**1.22E+01**	**1.22E+01**	**2.00E+01**	**1.96E+01**
19-CD	4	8.07E-01	8.07E-01	**1.20E+00**	**1.29E+00**
21-CD	5	5.66E-02	5.66E-02	5.80E-02	3.03E-02
22-CD	5	7.00E-01	7.00E-01	7.30E-01	3.75E-01
23-CD	5	1.54E-01	1.54E-01	1.60E-01	8.22E-02
24-CD	5	**8.76E+02**	**8.76E+02**	**1.60E+02**	**4.69E+02**
26-CD	4	**3.03E+01**	**3.03E+01**	**1.60E+01**	**1.62E+01**
27-CD	4	**1.16E+01**	**1.16E+01**	**6.30E+00**	**6.28E+00**

Table A-4. Risk values, dynamic risk assessment approach vs. the original data

APPENDIX B

Dynamic Risk Assessment of an Offshore Process facility

B.1. Separator:

Years	F2	S2	F3	S3	F4	S4	F5	S5	F6	S6	F7	S7	F8	S8	F9	S9	F10	S10	F11	S11
1	30	36	32	4	29	33	26	7	42	13	16	26	19	7	23	12	9	14	0	9
2	57	67	59	8	59	57	44	13	81	22	28	53	38	15	40	26	16	24	0	16
3	84	97	87	10	88	83	63	20	121	30	41	80	55	25	59	37	25	34	0	25
4	111	126	112	14	114	109	85	24	161	38	57	104	73	31	79	51	35	44	0	35
5	131	149	132	17	132	131	102	29	188	46	69	119	84	35	95	58	43	52	0	43

Table B-1. Number of failure/success of separator safety systems in the 5 year period

Event	a+F					b+S					Mean Value				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
2	40	67	94	121	141	426	457	487	516	539	0.0858	0.1279	0.1618	0.1900	0.2074
3	41	68	96	121	141	445	449	451	455	458	0.0844	0.1315	0.1755	0.2101	0.2354
4	40	70	99	125	143	572	596	622	648	670	0.0654	0.1051	0.1373	0.1617	0.1759
5	38	56	75	97	114	595	601	608	612	617	0.0600	0.0852	0.1098	0.1368	0.1560
6	62	101	141	181	208	278.71	287.71	295.71	303.71	311.71	0.1820	0.2598	0.3229	0.3734	0.4002
7	26	38	51	67	79	516	543	570	594	609	0.0480	0.0654	0.0821	0.1014	0.1148
8	99	118	135	153	164	53260.33	53268.33	53278.33	53284.33	53288.33	0.0019	0.0022	0.0025	0.0029	0.0031
9	33	50	69	89	105	502	516	527	541	548	0.0617	0.0883	0.1158	0.1413	0.1608
10	18	25	34	44	52	65	75	85	95	103	0.2169	0.2500	0.2857	0.3165	0.3355
11	2	2	2	2	2	17	24	33	43	51	0.1053	0.0769	0.0571	0.0444	0.0377

Table B-2. Posterior parameter of beta distribution and mean value for separator safety systems over the 5 year period

End-state	Category	Severity level	Dollar value	Prior Frequency	Posterior Frequency				
					1	2	3	4	5
1	A	1	$10,000.00	9.56E-01	8.37E-01	7.57E-01	6.91E-01	6.40E-01	6.06E-01
2	A	1	$10,000.00	1.87E-02	6.78E-02	9.39E-02	1.13E-01	1.23E-01	1.30E-01
3	A	1	$10,000.00	3.55E-04	3.54E-03	6.48E-03	9.44E-03	1.22E-02	1.44E-02
4	A	1	$10,000.00	2.62E-05	7.48E-04	2.12E-03	4.12E-03	6.53E-03	8.47E-03
5	A	1	$10,000.00	3.85E-08	1.31E-06	4.28E-06	9.23E-06	1.61E-05	2.19E-05
6	B	2	$100,000.00	6.69E-10	6.72E-08	3.11E-07	8.63E-07	1.81E-06	2.79E-06
7	B	2	$100,000.00	9.44E-11	1.66E-08	9.57E-08	3.26E-07	8.01E-07	1.35E-06
8	C	4	$3,000,000.00	2.36E-11	1.96E-09	7.98E-09	1.97E-08	3.73E-08	5.31E-08
9	A	1	$10,000.00	5.24E-07	3.54E-05	1.36E-04	3.27E-04	6.34E-04	9.25E-04
10	B	2	$100,000.00	9.10E-09	1.82E-06	9.85E-06	3.06E-05	7.13E-05	1.18E-04
11	B	2	$100,000.00	1.28E-09	4.52E-07	3.03E-06	1.15E-05	3.16E-05	5.72E-05
12	C	4	$3,000,000.00	3.21E-10	5.32E-08	2.53E-07	6.98E-07	1.47E-06	2.24E-06
13	A	1	$10,000.00	3.63E-04	4.12E-03	8.92E-03	1.37E-02	1.72E-02	1.97E-02
14	A	1	$10,000.00	2.67E-05	8.72E-04	2.92E-03	5.97E-03	9.21E-03	1.16E-02
15	B	2	$100,000.00	3.93E-08	1.52E-06	5.90E-06	1.34E-05	2.27E-05	2.99E-05
16	B	2	$100,000.00	6.82E-10	7.83E-08	4.29E-07	1.25E-06	2.55E-06	3.81E-06
17	B	2	$100,000.00	9.63E-11	1.94E-08	1.32E-07	4.72E-07	1.13E-06	1.85E-06
18	C	4	$3,000,000.00	2.41E-11	2.28E-09	1.10E-08	2.86E-08	5.25E-08	7.26E-08
19	A	1	$10,000.00	5.35E-07	4.13E-05	1.87E-04	4.74E-04	8.94E-04	1.27E-03
20	B	2	$100,000.00	9.28E-09	2.13E-06	1.36E-05	4.43E-05	1.01E-04	1.61E-04
21	B	2	$100,000.00	1.31E-09	5.27E-07	4.18E-06	1.67E-05	4.45E-05	7.83E-05
22	C	4	$3,000,000.00	3.28E-10	6.20E-08	3.48E-07	1.01E-06	2.07E-06	3.07E-06
23	A	1	$10,000.00	2.40E-02	7.54E-02	1.05E-01	1.24E-01	1.37E-01	1.44E-01
24	A	1	$10,000.00	4.56E-04	3.94E-03	7.22E-03	1.04E-02	1.37E-02	1.60E-02
25	A	1	$10,000.00	3.36E-05	8.33E-04	2.36E-03	4.53E-03	7.29E-03	9.41E-03
26	A	1	$10,000.00	4.94E-08	1.45E-06	4.77E-06	1.02E-05	1.80E-05	2.43E-05
27	B	2	$100,000.00	8.57E-10	7.48E-08	3.47E-07	9.49E-07	2.02E-06	3.10E-06
28	B	2	$100,000.00	1.21E-10	1.85E-08	1.07E-07	3.58E-07	8.94E-07	1.50E-06
29	C	4	$3,000,000.00	3.03E-11	2.18E-09	8.89E-09	2.17E-08	4.16E-08	5.90E-08
30	A	1	$10,000.00	6.72E-07	3.94E-05	1.51E-04	3.59E-04	7.08E-04	1.03E-03
31	B	2	$100,000.00	1.17E-08	2.03E-06	1.10E-05	3.36E-05	7.96E-05	1.31E-04
32	B	2	$100,000.00	1.65E-09	5.03E-07	3.38E-06	1.27E-05	3.52E-05	6.36E-05
33	C	4	$3,000,000.00	4.12E-10	5.92E-08	2.82E-07	7.68E-07	1.64E-06	2.49E-06
34	A	1	$10,000.00	4.65E-04	4.59E-03	9.95E-03	1.50E-02	1.92E-02	2.19E-02
35	A	1	$10,000.00	3.42E-05	9.70E-04	3.26E-03	6.57E-03	1.03E-02	1.29E-02
36	A	1	$10,000.00	5.04E-08	1.69E-06	6.58E-06	1.47E-05	2.53E-05	3.33E-05
37	B	2	$100,000.00	8.75E-10	8.71E-08	4.78E-07	1.38E-06	2.85E-06	4.24E-06

End-state	Category	Severity level	Dollar value	Prior Frequency	Posterior Frequency				
					1	2	3	4	5
38	B	2	$100,000.00	1.23E-10	2.16E-08	1.47E-07	5.19E-07	1.26E-06	2.06E-06
39	C	4	$3,000,000.00	3.09E-11	2.54E-09	1.23E-08	3.15E-08	5.87E-08	8.07E-08
40	A	1	$10,000.00	6.86E-07	4.60E-05	2.08E-04	5.21E-04	9.98E-04	1.41E-03
41	B	2	$100,000.00	1.19E-08	2.37E-06	1.51E-05	4.87E-05	1.12E-04	1.79E-04
42	B	2	$100,000.00	1.68E-09	5.86E-07	4.66E-06	1.84E-05	4.97E-05	8.70E-05
43	C	4	$3,000,000.00	4.20E-10	6.90E-08	3.88E-07	1.11E-06	2.31E-06	3.41E-06

Table B-3. End-state probabilities for the separator over the 5 year period

End-state	Category	Severity level	Dollar value	Prior Risk	Posterior Risk				
					1	2	3	4	5
1	A	1	$10,000.00	9.56E+03	8.37E+03	7.57E+03	6.91E+03	6.40E+03	6.06E+03
2	A	1	$10,000.00	1.87E+02	6.78E+02	9.39E+02	1.13E+03	1.23E+03	1.30E+03
3	A	1	$10,000.00	3.55E+00	3.54E+01	6.48E+01	9.44E+01	1.22E+02	1.44E+02
4	A	1	$10,000.00	2.62E-01	7.48E+00	2.12E+01	4.12E+01	6.53E+01	8.47E+01
5	A	1	$10,000.00	3.85E-04	1.31E-02	4.28E-02	9.23E-02	1.61E-01	2.19E-01
6	B	2	$100,000.00	6.69E-05	6.72E-03	3.11E-02	8.63E-02	1.81E-01	2.79E-01
7	B	2	$100,000.00	9.44E-06	1.66E-03	9.57E-03	3.26E-02	8.01E-02	1.35E-01
8	C	4	$3,000,000.00	7.08E-05	5.88E-03	2.39E-02	5.92E-02	1.12E-01	1.59E-01
9	A	1	$10,000.00	5.24E-03	3.54E-01	1.36E+00	3.27E+00	6.34E+00	9.25E+00
10	B	2	$100,000.00	9.10E-04	1.82E-01	9.85E-01	3.06E+00	7.13E+00	1.18E+01
11	B	2	$100,000.00	1.28E-04	4.52E-02	3.03E-01	1.15E+00	3.16E+00	5.72E+00
12	C	4	$3,000,000.00	9.63E-04	1.60E-01	7.58E-01	2.10E+00	4.40E+00	6.73E+00
13	A	1	$10,000.00	3.63E+00	4.12E+01	8.92E+01	1.37E+02	1.72E+02	1.97E+02
14	A	1	$10,000.00	2.67E-01	8.72E+00	2.92E+01	5.97E+01	9.21E+01	1.16E+02
15	B	2	$100,000.00	3.93E-03	1.52E-01	5.90E-01	1.34E+00	2.27E+00	2.99E+00
16	B	2	$100,000.00	6.82E-05	7.83E-03	4.29E-02	1.25E-01	2.55E-01	3.81E-01
17	B	2	$100,000.00	9.63E-06	1.94E-03	1.32E-02	4.72E-02	1.13E-01	1.85E-01
18	C	4	$3,000,000.00	7.22E-05	6.84E-03	3.30E-02	8.58E-02	1.58E-01	2.18E-01
19	A	1	$10,000.00	5.35E-03	4.13E-01	1.87E+00	4.74E+00	8.94E+00	1.27E+01
20	B	2	$100,000.00	9.28E-04	2.13E-01	1.36E+00	4.43E+00	1.01E+01	1.61E+01
21	B	2	$100,000.00	1.31E-04	5.27E-02	4.18E-01	1.67E+00	4.45E+00	7.83E+00
22	C	4	$3,000,000.00	9.83E-04	1.86E-01	1.04E+00	3.04E+00	6.21E+00	9.21E+00
23	A	1	$10,000.00	2.40E+02	7.54E+02	1.05E+03	1.24E+03	1.37E+03	1.44E+03
24	A	1	$10,000.00	4.56E+00	3.94E+01	7.22E+01	1.04E+02	1.37E+02	1.60E+02

End-state	Category	Severity level	Dollar value	Prior Risk	Posterior Risk				
					1	2	3	4	5
25	A	1	$10,000.00	3.36E-01	8.33E+00	2.36E+01	4.53E+01	7.29E+01	9.41E+01
26	A	1	$10,000.00	4.94E-04	1.45E-02	4.77E-02	1.02E-01	1.80E-01	2.43E-01
27	B	2	$100,000.00	8.57E-05	7.48E-03	3.47E-02	9.49E-02	2.02E-01	3.10E-01
28	B	2	$100,000.00	1.21E-05	1.85E-03	1.07E-02	3.58E-02	8.94E-02	1.50E-01
29	C	4	$3,000,000.00	9.08E-05	6.54E-03	2.67E-02	6.51E-02	1.25E-01	1.77E-01
30	A	1	$10,000.00	6.72E-03	3.94E-01	1.51E+00	3.59E+00	7.08E+00	1.03E+01
31	B	2	$100,000.00	1.17E-03	2.03E-01	1.10E+00	3.36E+00	7.96E+00	1.31E+01
32	B	2	$100,000.00	1.65E-04	5.03E-02	3.38E-01	1.27E+00	3.52E+00	6.36E+00
33	C	4	$3,000,000.00	1.23E-03	1.78E-01	8.45E-01	2.30E+00	4.92E+00	7.48E+00
34	A	1	$10,000.00	4.65E+00	4.59E+01	9.95E+01	1.50E+02	1.92E+02	2.19E+02
35	A	1	$10,000.00	3.42E-01	9.70E+00	3.26E+01	6.57E+01	1.03E+02	1.29E+02
36	A	1	$10,000.00	5.04E-04	1.69E-02	6.58E-02	1.47E-01	2.53E-01	3.33E-01
37	B	2	$100,000.00	8.75E-05	8.71E-03	4.78E-02	1.38E-01	2.85E-01	4.24E-01
38	B	2	$100,000.00	1.23E-05	2.16E-03	1.47E-02	5.19E-02	1.26E-01	2.06E-01
39	C	4	$3,000,000.00	9.26E-05	7.62E-03	3.68E-02	9.44E-02	1.76E-01	2.42E-01
40	A	1	$10,000.00	6.86E-03	4.60E-01	2.08E+00	5.21E+00	9.98E+00	1.41E+01
41	B	2	$100,000.00	1.19E-03	2.37E-01	1.51E+00	4.87E+00	1.12E+01	1.79E+01
42	B	2	$100,000.00	1.68E-04	5.86E-02	4.66E-01	1.84E+00	4.97E+00	8.70E+00
43	C	4	$3,000,000.00	1.26E-03	2.07E-01	1.16E+00	3.34E+00	6.93E+00	1.02E+01

Table B-4. Risk values for the separator over the 5 year period

B.2. Compressor:

Years	F2	S2	F3	S3	F4	S4	F5	S5	F6	S6	F7	S7	F8	S8	F9	S9
1	7	19	10	2	13	4	0	13	6	7	3	4	5	4	0	5
2	14	35	17	4	24	7	0	24	11	13	7	6	9	9	0	9
3	24	54	25	5	39	10	1	38	17	21	13	8	13	17	1	12
4	32	70	31	7	51	12	2	49	22	27	18	9	18	22	3	15
5	35	77	34	8	56	13	2	54	24	30	20	10	22	22	3	19

Table B-5. Number of failure/success of compressor safety systems in the 5 year period

Event	a+F					b+S					Mean value				
	1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
2	17	24	34	42	45	409	425	444	460	467	0.0399	0.0535	0.0711	0.0837	0.0879
3	19	26	34	40	43	443	445	446	448	449	0.0411	0.0552	0.0708	0.0820	0.0874
4	24	35	50	62	67	543	546	549	551	552	0.0423	0.0602	0.0835	0.1011	0.1082
5	1	1	2	3	3	112	123	137	148	153	0.0088	0.0081	0.0144	0.0199	0.0192
6	16	21	27	32	34	497	503	511	517	520	0.0312	0.0401	0.0502	0.0583	0.0614
7	83	87	93	98	100	53257.33	53259.33	53261.33	53262.33	53263.33	0.0016	0.0016	0.0017	0.0018	0.0019
8	14	18	22	27	31	55	60	68	73	73	0.2029	0.2308	0.2444	0.2700	0.2981
9	2	2	3	5	5	13	17	20	23	27	0.1333	0.1053	0.1304	0.1786	0.1563

Table B-6. Posterior parameter of beta distribution and mean value for compressor safety systems over the 5 year period

End-state	Category	Severity level	Dollar value	Prior Frequency	Posterior Frequency				
					1	2	3	4	5
1	A	1	$10,000.00	9.56E-01	9.21E-01	8.94E-01	8.63E-01	8.41E-01	8.32E-01
2	A	1	$10,000.00	1.91E-02	3.78E-02	4.91E-02	6.03E-02	6.75E-02	7.11E-02
3	A	1	$10,000.00	3.78E-04	1.60E-03	2.99E-03	5.13E-03	7.00E-03	7.93E-03
4	B	2	$100,000.00	4.82E-07	1.99E-06	3.76E-06	6.77E-06	9.40E-06	1.04E-05
5	B	2	$100,000.00	6.81E-08	4.39E-07	1.01E-06	1.90E-06	2.86E-06	3.74E-06
6	C	2	$100,000.00	1.70E-08	6.76E-08	1.19E-07	2.86E-07	6.21E-07	6.93E-07
7	B	2	$100,000.00	6.56E-06	4.12E-05	9.63E-05	2.05E-04	3.17E-04	3.65E-04
8	B	2	$100,000.00	9.27E-07	9.09E-06	2.58E-05	5.77E-05	9.63E-05	1.31E-04
9	C	2	$100,000.00	2.32E-07	1.40E-06	3.04E-06	8.66E-06	2.09E-05	2.42E-05
10	C	2	$100,000.00	3.90E-06	1.48E-05	2.54E-05	7.90E-05	1.51E-04	1.66E-04
11	A	1	$10,000.00	2.45E-02	3.82E-02	5.02E-02	6.52E-02	7.52E-02	7.84E-02
12	A	1	$10,000.00	4.84E-04	1.62E-03	3.06E-03	5.55E-03	7.80E-03	8.74E-03
13	B	2	$100,000.00	6.19E-07	2.01E-06	3.85E-06	7.32E-06	1.05E-05	1.15E-05
14	B	2	$100,000.00	8.73E-08	4.44E-07	1.03E-06	2.06E-06	3.18E-06	4.13E-06
15	C	2	$100,000.00	2.18E-08	6.83E-08	1.21E-07	3.09E-07	6.92E-07	7.64E-07
16	B	2	$100,000.00	8.42E-06	4.16E-05	9.85E-05	2.22E-04	3.53E-04	4.02E-04
17	B	2	$100,000.00	1.19E-06	9.18E-06	2.64E-05	6.24E-05	1.07E-04	1.44E-04
18	C	2	$100,000.00	2.97E-07	1.41E-06	3.11E-06	9.36E-06	2.33E-05	2.67E-05
19	C	2	$100,000.00	5.00E-06	1.49E-05	2.60E-05	8.54E-05	1.68E-04	1.83E-04

Table B-7. End-state probabilities for the compressor over the 5 year period

End-state	Category	Severity level	Dollar value	Prior Risk	Posterior Risk				
					1	2	3	4	5
1	A	1	$10,000.00	9.56E+03	9.21E+03	8.94E+03	8.63E+03	8.41E+03	8.32E+03
2	A	1	$10,000.00	1.91E+02	3.78E+02	4.91E+02	6.03E+02	6.75E+02	7.11E+02
3	A	1	$10,000.00	3.78E+00	1.60E+01	2.99E+01	5.13E+01	7.00E+01	7.93E+01
4	B	2	$100,000.00	4.82E-02	1.99E-01	3.76E-01	6.77E-01	9.40E-01	1.04E+00
5	B	2	$100,000.00	6.81E-03	4.39E-02	1.01E-01	1.90E-01	2.86E-01	3.74E-01
6	C	2	$100,000.00	1.70E-03	6.76E-03	1.19E-02	2.86E-02	6.21E-02	6.93E-02
7	B	2	$100,000.00	6.56E-01	4.12E+00	9.63E+00	2.05E+01	3.17E+01	3.65E+01
8	B	2	$100,000.00	9.27E-02	9.09E-01	2.58E+00	5.77E+00	9.63E+00	1.31E+01
9	C	2	$100,000.00	2.32E-02	1.40E-01	3.04E-01	8.66E-01	2.09E+00	2.42E+00
10	C	2	$100,000.00	3.90E-01	1.48E+00	2.54E+00	7.90E+00	1.51E+01	1.66E+01
11	A	1	$10,000.00	2.45E+02	3.82E+02	5.02E+02	6.52E+02	7.52E+02	7.84E+02
12	A	1	$10,000.00	4.84E+00	1.62E+01	3.06E+01	5.55E+01	7.80E+01	8.74E+01
13	B	2	$100,000.00	6.19E-02	2.01E-01	3.85E-01	7.32E-01	1.05E+00	1.15E+00
14	B	2	$100,000.00	8.73E-03	4.44E-02	1.03E-01	2.06E-01	3.18E-01	4.13E-01
15	C	2	$100,000.00	2.18E-03	6.83E-03	1.21E-02	3.09E-02	6.92E-02	7.64E-02
16	B	2	$100,000.00	8.42E-01	4.16E+00	9.85E+00	2.22E+01	3.53E+01	4.02E+01
17	B	2	$100,000.00	1.19E-01	9.18E-01	2.64E+00	6.24E+00	1.07E+01	1.44E+01
18	C	2	$100,000.00	2.97E-02	1.41E-01	3.11E-01	9.36E-01	2.33E+00	2.67E+00
19	C	2	$100,000.00	5.00E-01	1.49E+00	2.60E+00	8.54E+00	1.68E+01	1.83E+01

Table B-8. Risk values for the compressor over the 5 year period

B.3. Flash Drum

Years	F2	S2	F3	S3	F4	S4	F5	S5	F6	S6	F7	S7	F8	S8	F9	S9	F10	S10
1	16	26	21	5	15	22	19	3	2	32	25	7	11	15	4	7	0	3
2	28	45	37	8	27	38	32	6	2	57	44	13	22	23	10	12	0	9
3	40	65	55	10	41	54	45	9	3	83	64	19	35	31	16	19	0	14
4	57	84	70	14	55	72	60	12	4	111	84	27	46	40	22	24	0	20
5	69	101	86	15	64	91	75	16	7	132	101	31	57	47	29	28	1	25

Table B-9. Number of failure/success of flash drum safety systems in the 5 year period

Event	a+F					b+S					Mean values				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
2	26.00	38.00	50.00	67.00	79.00	416.00	435.00	455.00	474.00	491.00	0.0705	0.0803	0.0990	0.1238	0.1386
3	30.00	46.00	64.00	79.00	95.00	446.00	449.00	451.00	455.00	456.00	0.0804	0.0929	0.1243	0.1479	0.1724
4	26.00	38.00	52.00	66.00	75.00	561.00	577.00	593.00	611.00	630.00	0.0705	0.0618	0.0806	0.0975	0.1064
5	29.00	42.00	55.00	70.00	85.00	493.00	496.00	499.00	502.00	506.00	0.0780	0.0781	0.0993	0.1224	0.1438
6	10.00	10.00	11.00	12.00	15.00	424.00	449.00	475.00	503.00	524.00	0.0283	0.0218	0.0226	0.0233	0.0278
7	34.00	53.00	73.00	93.00	110.00	448.00	454.00	460.00	468.00	472.00	0.0902	0.1045	0.1370	0.1658	0.1890
8	91.00	102.00	115.00	126.00	137.00	53268.33	53276.33	53284.33	53293.33	53300.33	0.2097	0.0019	0.0022	0.0024	0.0026
9	13.00	19.00	25.00	31.00	38.00	58.00	63.00	70.00	75.00	79.00	0.0365	0.2317	0.2632	0.2925	0.3248
10	2.00	2.00	2.00	2.00	3.00	11.00	17.00	22.00	28.00	33.00	0.0058	0.1053	0.0833	0.0667	0.0833

Table B-10. Posterior parameter of beta distribution and mean value for flash drum safety systems over the 5 year period

End-state	Category	Severity level	Dollar value	Prior Frequency	Posterior Frequency				
					1	2	3	4	5
1	A	1	$10,000.00	9.56E-01	8.55E-01	8.34E-01	7.89E-01	7.47E-01	7.13E-01
2	A	1	$10,000.00	1.87E-02	6.41E-02	7.39E-02	9.27E-02	1.03E-01	1.14E-01
3	A	1	$10,000.00	3.67E-04	4.79E-03	5.48E-03	8.62E-03	1.17E-02	1.50E-02
4	A	1	$10,000.00	7.48E-06	3.75E-04	6.39E-04	1.37E-03	2.31E-03	3.50E-03
5	B	2	$100,000.00	9.55E-09	9.59E-05	9.40E-07	2.17E-06	3.87E-06	6.07E-06
6	B	2	$100,000.00	1.35E-09	3.61E-06	2.54E-07	7.11E-07	1.49E-06	2.68E-06
7	C	2	$100,000.00	3.37E-10	2.11E-08	2.98E-08	6.46E-08	1.07E-07	2.43E-07
8	C	2	$100,000.00	7.64E-06	1.53E-04	1.36E-04	2.31E-04	3.34E-04	5.31E-04
9	A	1	$10,000.00	3.75E-04	4.66E-03	4.63E-03	7.61E-03	1.03E-02	1.25E-02
10	A	1	$10,000.00	7.63E-06	3.65E-04	5.39E-04	1.21E-03	2.04E-03	2.90E-03
11	B	2	$100,000.00	9.75E-09	9.33E-05	7.93E-07	1.92E-06	3.41E-06	5.03E-06
12	B	2	$100,000.00	1.38E-09	3.51E-06	2.14E-07	6.28E-07	1.32E-06	2.22E-06
13	C	2	$100,000.00	3.44E-10	2.05E-08	2.52E-08	5.71E-08	9.41E-08	2.01E-07
14	C	2	$100,000.00	7.80E-06	1.49E-04	1.15E-04	2.04E-04	2.94E-04	4.40E-04
15	A	1	$10,000.00	2.40E-02	6.04E-02	6.95E-02	8.20E-02	9.81E-02	1.06E-01
16	A	1	$10,000.00	4.71E-04	4.51E-03	5.15E-03	7.62E-03	1.11E-02	1.40E-02
17	A	1	$10,000.00	9.59E-06	3.54E-04	6.01E-04	1.21E-03	2.21E-03	3.26E-03
18	B	2	$100,000.00	1.22E-08	9.04E-05	8.83E-07	1.92E-06	3.70E-06	5.67E-06
19	B	2	$100,000.00	1.73E-09	3.41E-06	2.38E-07	6.28E-07	1.43E-06	2.50E-06
20	C	2	$100,000.00	4.32E-10	1.99E-08	2.80E-08	5.71E-08	1.02E-07	2.27E-07
21	C	2	$100,000.00	9.80E-06	1.45E-04	1.28E-04	2.05E-04	3.19E-04	4.96E-04
22	A	1	$10,000.00	4.80E-04	4.39E-03	4.35E-03	6.73E-03	9.84E-03	1.16E-02
23	A	1	$10,000.00	9.79E-06	3.44E-04	5.07E-04	1.07E-03	1.95E-03	2.70E-03
24	B	2	$100,000.00	1.25E-08	8.79E-05	7.45E-07	1.70E-06	3.26E-06	4.69E-06
25	B	2	$100,000.00	1.76E-09	3.31E-06	2.01E-07	5.55E-07	1.26E-06	2.07E-06
26	C	2	$100,000.00	4.41E-10	1.93E-08	2.37E-08	5.05E-08	8.99E-08	1.88E-07
27	C	2	$100,000.00	1.00E-05	1.41E-04	1.08E-04	1.81E-04	2.81E-04	4.10E-04

Table B-11. End-state probabilities for the flash drum over the 5 year period

End-state	Category	Severity level	Dollar value	Prior Risk	Posterior Risk				
					1	2	3	4	5
1	A	1	$10,000.00	9.56E+03	8.55E+03	8.34E+03	7.89E+03	7.47E+03	7.13E+03
2	A	1	$10,000.00	1.87E+02	6.41E+02	7.39E+02	9.27E+02	1.03E+03	1.14E+03
3	A	1	$10,000.00	3.67E+00	4.79E+01	5.48E+01	8.62E+01	1.17E+02	1.50E+02
4	A	1	$10,000.00	7.48E-02	3.75E+00	6.39E+00	1.37E+01	2.31E+01	3.50E+01
5	B	2	$100,000.00	9.55E-04	9.59E+00	9.40E-02	2.17E-01	3.87E-01	6.07E-01
6	B	2	$100,000.00	1.35E-04	3.61E-01	2.54E-02	7.11E-02	1.49E-01	2.68E-01
7	C	2	$100,000.00	3.37E-05	2.11E-03	2.98E-03	6.46E-03	1.07E-02	2.43E-02
8	C	2	$100,000.00	7.64E-01	1.53E+01	1.36E+01	2.31E+01	3.34E+01	5.31E+01
9	A	1	$10,000.00	3.75E+00	4.66E+01	4.63E+01	7.61E+01	1.03E+02	1.25E+02
10	A	1	$10,000.00	7.63E-02	3.65E+00	5.39E+00	1.21E+01	2.04E+01	2.90E+01
11	B	2	$100,000.00	9.75E-04	9.33E+00	7.93E-02	1.92E-01	3.41E-01	5.03E-01
12	B	2	$100,000.00	1.38E-04	3.51E-01	2.14E-02	6.28E-02	1.32E-01	2.22E-01
13	C	2	$100,000.00	3.44E-05	2.05E-03	2.52E-03	5.71E-03	9.41E-03	2.01E-02
14	C	2	$100,000.00	7.80E-01	1.49E+01	1.15E+01	2.04E+01	2.94E+01	4.40E+01
15	A	1	$10,000.00	2.40E+02	6.04E+02	6.95E+02	8.20E+02	9.81E+02	1.06E+03
16	A	1	$10,000.00	4.71E+00	4.51E+01	5.15E+01	7.62E+01	1.11E+02	1.40E+02
17	A	1	$10,000.00	9.59E-02	3.54E+00	6.01E+00	1.21E+01	2.21E+01	3.26E+01
18	B	2	$100,000.00	1.22E-03	9.04E+00	8.83E-02	1.92E-01	3.70E-01	5.67E-01
19	B	2	$100,000.00	1.73E-04	3.41E-01	2.38E-02	6.28E-02	1.43E-01	2.50E-01
20	C	2	$100,000.00	4.32E-05	1.99E-03	2.80E-03	5.71E-03	1.02E-02	2.27E-02
21	C	2	$100,000.00	9.80E-01	1.45E+01	1.28E+01	2.05E+01	3.19E+01	4.96E+01
22	A	1	$10,000.00	4.80E+00	4.39E+01	4.35E+01	6.73E+01	9.84E+01	1.16E+02
23	A	1	$10,000.00	9.79E-02	3.44E+00	5.07E+00	1.07E+01	1.95E+01	2.70E+01
24	B	2	$100,000.00	1.25E-03	8.79E+00	7.45E-02	1.70E-01	3.26E-01	4.69E-01
25	B	2	$100,000.00	1.76E-04	3.31E-01	2.01E-02	5.55E-02	1.26E-01	2.07E-01
26	C	2	$100,000.00	4.41E-05	1.93E-03	2.37E-03	5.05E-03	8.99E-03	1.88E-02
27	C	2	$100,000.00	1.00E+00	1.41E+01	1.08E+01	1.81E+01	2.81E+01	4.10E+01

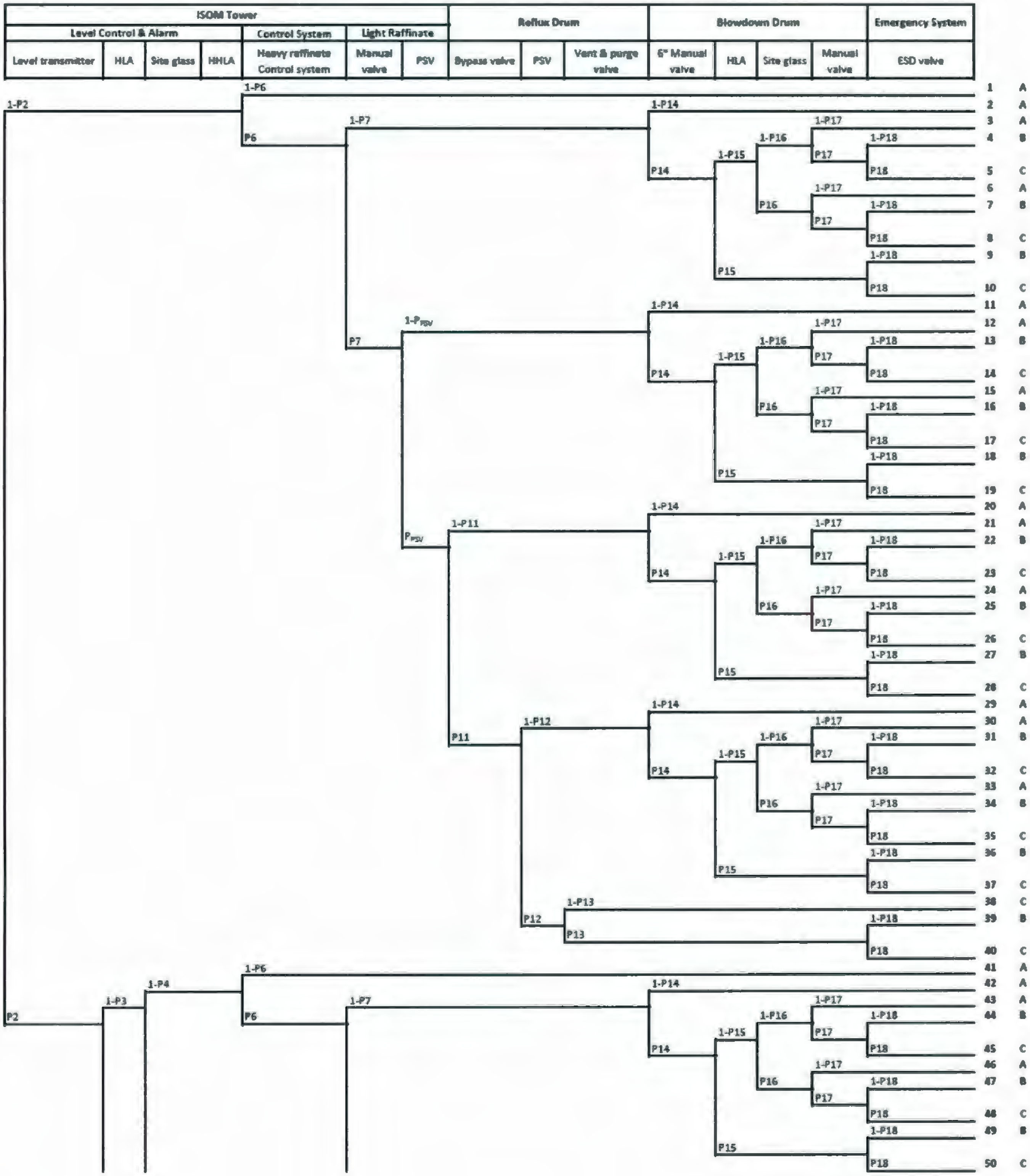
Table B-12. Risk values for the flash drum over the 5 year period

APPENDIX C

Modelling of BP Texas Refinery Accident using Dynamic Risk Assessment Approach

Success/Failure	Years										
Safety Systems	1	2	3	4	5	6	7	8	9	10	11
F2	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0
F3	0	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0	0
F4	0	0	0	0	0	0	0	0	0	0	0
S4	0	0	0	0	0	0	0	0	0	0	0
F5	0	0	0	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	0	0	0
F6	0	0	0	0	0	0	0	0	0	0	0
S6	0	0	0	0	0	0	0	0	0	0	0
F7	0	0	0	0	0	0	0	0	0	0	0
S7	0	0	0	0	0	0	0	0	0	0	0
F_{PSV}	0	0	0	0	0	0	0	0	0	0	0
S_{PSV}	0	0	0	0	0	0	0	0	0	0	0
F11	0	0	0	0	0	0	0	0	0	0	0
S11	0	0	0	0	0	0	0	0	0	0	0
F12	0	0	0	0	0	0	0	0	0	0	0
S12	0	0	0	0	0	0	0	0	0	0	0
F13	0	0	0	0	0	0	0	0	0	0	0
S13	0	0	0	0	0	0	0	0	0	0	0
F14	0	0	0	0	0	0	0	0	0	0	0
S14	0	0	0	0	0	0	0	0	0	0	0
F15	0	0	0	0	0	0	0	0	0	0	0
S15	0	0	0	0	0	0	0	0	0	0	0
F16	0	0	0	0	0	0	0	0	0	0	0
S16	0	0	0	0	0	0	0	0	0	0	0
F17	0	0	0	0	0	0	0	0	0	0	0
S17	0	0	0	0	0	0	0	0	0	0	0
F18	0	0	0	0	0	0	0	0	0	0	0
S18	0	0	0	0	0	0	0	0	0	0	0

Table C-1. Number of failure/success of the ISOM unit safety systems over the 11 year period


ISOM Tower
Level Control & Alarm
Control System
Light Raffinate
Level transmitter
HLA
Site glass
HHLA
Heavy raffinate Control system
Manual valve
PSV
Reflux Drum
Bypass valve
PSV
Vent & purge valve
Blowdown Drum
6" Manual valve
HLA
Site glass
Manual valve
Emergency System
ESD valve
1-P2
P2
1-P3
1-P4
1-P6
P6
1-P7
P7
1-P_PSV
P_PSV
1-P11
P11
1-P12
P12
1-P13
P13
1-P14
P14
1-P15
P15
1-P16
P16
1-P17
P17
1-P18
P18
1 A
2 A
3 A
4 B
5 C
6 A
7 B
8 C
9 B
10 C
11 A
12 A
13 B
14 C
15 A
16 B
17 C
18 B
19 C
20 A
21 A
22 B
23 C
24 A
25 B
26 C
27 B
28 C
29 A
30 A
31 B
32 C
33 A
34 B
35 C
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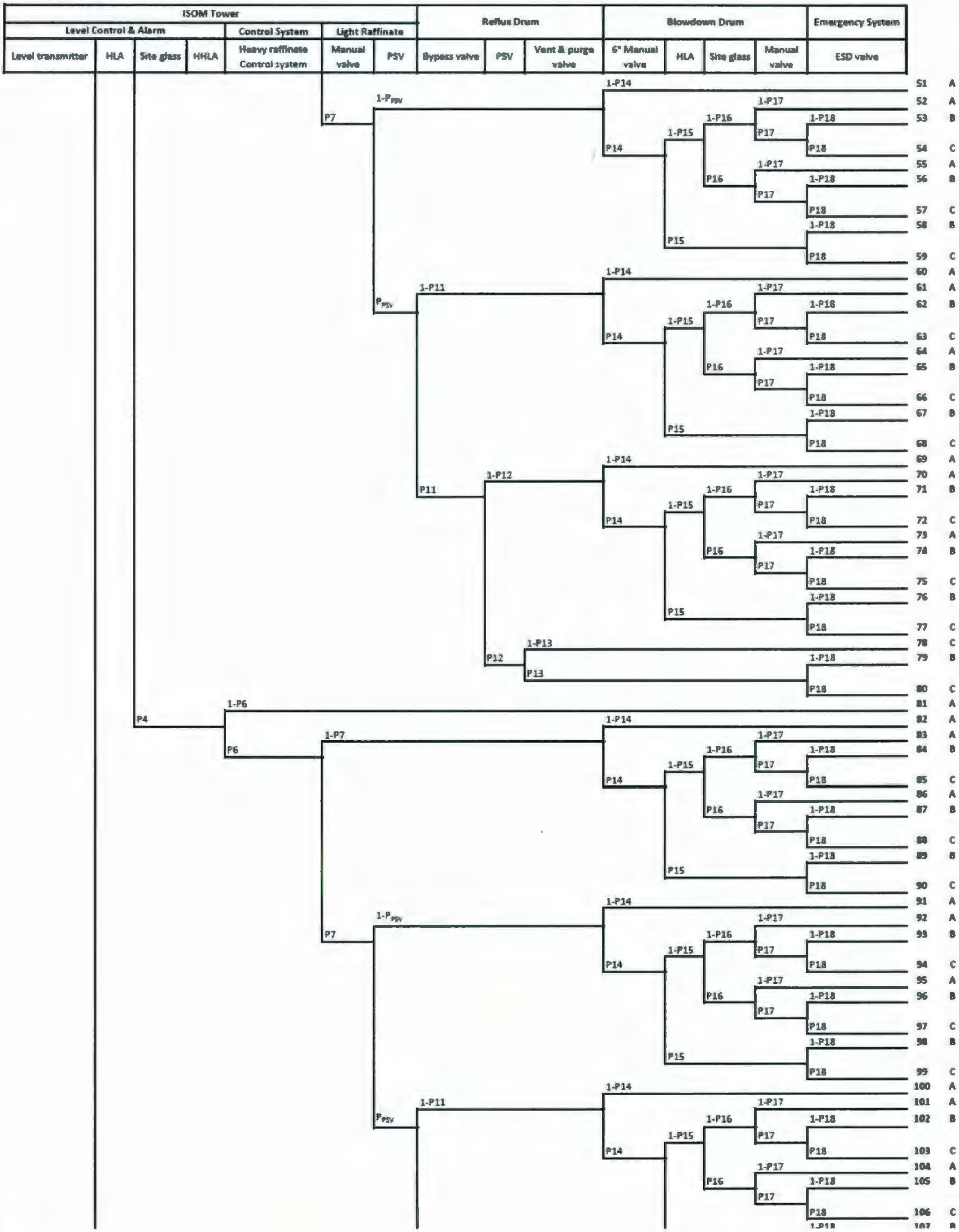
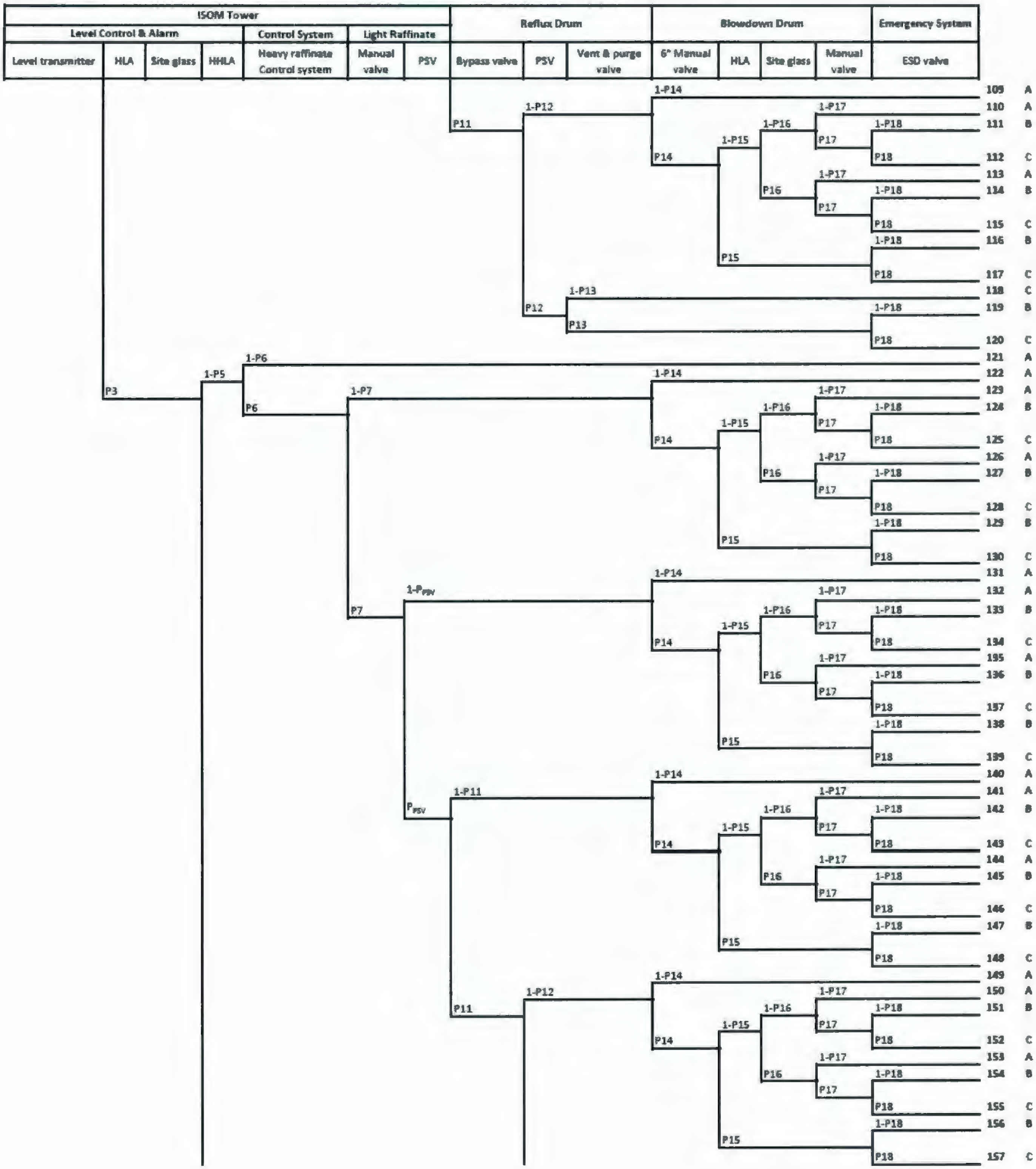
49 B
50 C


ISOM Tower
Level Control & Alarm
Control System
Light Raffinate
Reflux Drum
Blowdown Drum
Emergency System
Level transmitter
HLA
Site glass
HHLA
Heavy raffinate Control system
Manual valve
PSV
Bypass valve
PSV
Vent & purge valve
6" Manual valve
HLA
Site glass
Manual valve
ESD valve
P4
1-P6
P6
1-P7
P7
1-P_{PSV}
P_{PSV}
1-P11
P11
1-P12
P12
1-P13
P13
1-P14
P14
1-P15
P15
1-P16
P16
1-P17
P17
1-P18
P18
51 A
52 A
53 B
54 C
55 A
56 B
57 C
58 B
59 C
60 A
61 A
62 B
63 C
64 A
65 B
66 C
67 B
68 C
69 A
70 A
71 B
72 C
73 A
74 B
75 C
76 B
77 C
78 C
79 B
80 C
81 A
82 A
83 A
84 B
85 C
86 A
87 B
88 C
89 B
90 C
91 A
92 A
93 B
94 C
95 A
96 B
97 C
98 B
99 C
100 A
101 A
102 B
103 C
104 A
105 B
106 C


ISOM Tower
Level Control & Alarm
Control System
Light Raffinate
Reflux Drum
Blowdown Drum
Emergency System
Level transmitter
HLA
Site glass
HHLA
Heavy raffinate Control system
Manual valve
PSV
Bypass valve
PSV
Vent & purge valve
6" Manual valve
HLA
Site glass
Manual valve
ESD valve
109 A
110 A
111 B
112 C
113 A
114 B
115 C
116 B
117 C
118 C
119 B
120 C
121 A
122 A
123 A
124 B
125 C
126 A
127 B
128 C
129 B
130 C
131 A
132 A
133 B
134 C
135 A
136 B
137 C
138 B
139 C
140 A
141 A
142 B
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154 B
155 C
156 B
157 C

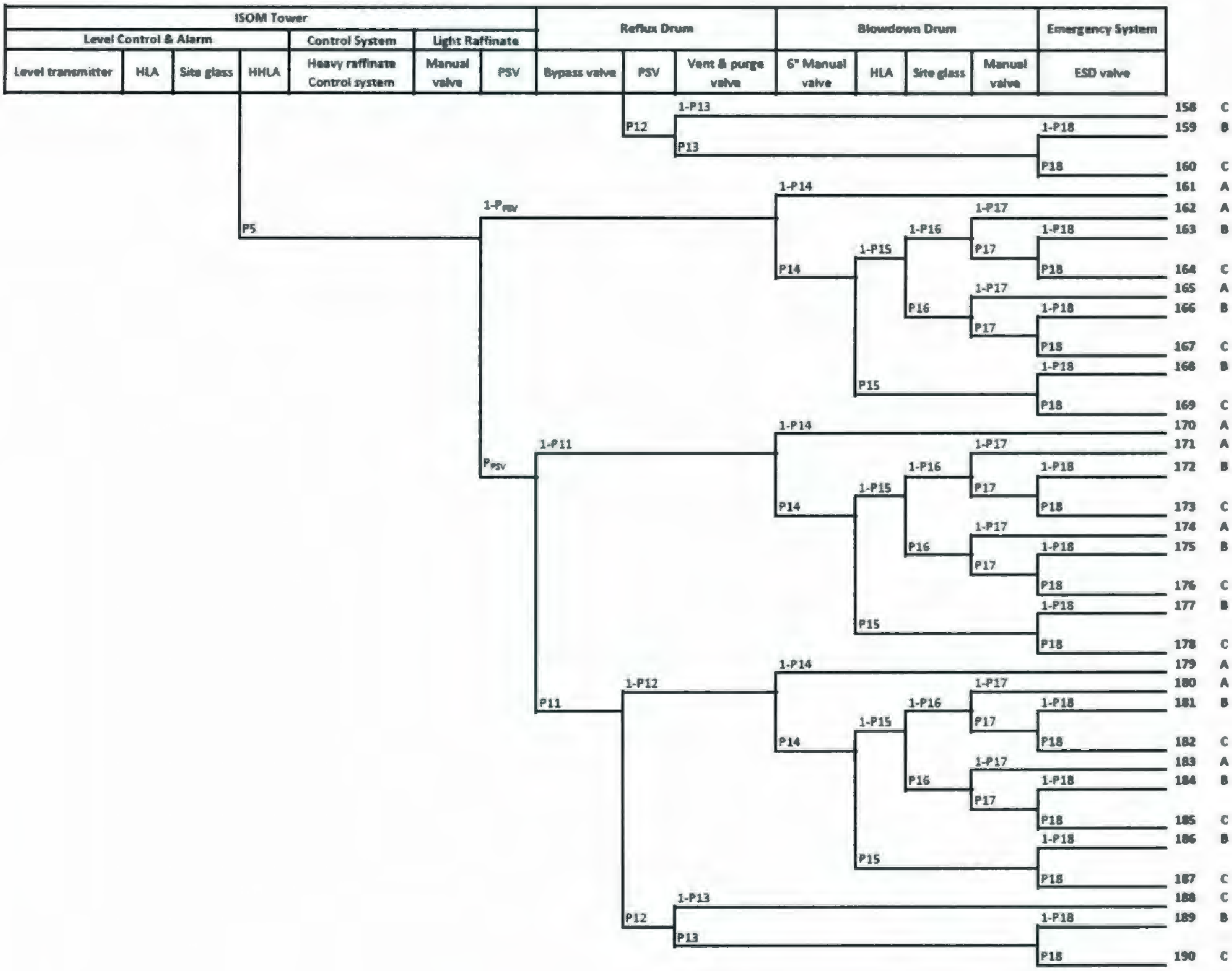

Figure C-1. Event tree of the ISOM unit

End-State	Class	Severity	Dollar value	Prior Frequency	Posterior Frequency										
				0	1	2	3	4	5	6	7	8	9	10	11
1	A	1	$10,000.00	9.70E-01	9.62E-01	9.56E-01	9.54E-01	9.50E-01	9.46E-01	9.40E-01	9.33E-01	9.29E-01	9.24E-01	9.19E-01	9.11E-01
2	A	1	$10,000.00	1.27E-02	1.18E-02	1.34E-02	1.27E-02	1.16E-02	1.07E-02	1.03E-02	9.59E-03	9.65E-03	1.03E-02	1.03E-02	1.03E-02
3	A	1	$10,000.00	1.94E-03	3.18E-03	4.79E-03	4.71E-03	4.74E-03	4.49E-03	4.60E-03	4.65E-03	4.71E-03	4.97E-03	5.12E-03	5.01E-03
4	B	2	$100,000.00	3.88E-04	7.68E-04	1.55E-03	1.96E-03	2.49E-03	3.06E-03	3.91E-03	3.95E-03	4.94E-03	6.25E-03	7.06E-03	7.78E-03
5	C	4	$10,000,000.00	9.69E-05	4.26E-04	8.46E-04	9.80E-04	1.07E-03	1.43E-03	1.84E-03	1.87E-03	2.12E-03	2.44E-03	2.54E-03	2.88E-03
6	A	1	$10,000.00	2.15E-04	3.50E-04	5.79E-04	5.63E-04	5.60E-04	5.20E-04	5.75E-04	5.82E-04	5.76E-04	7.10E-04	7.24E-04	8.10E-04
7	B	2	$100,000.00	4.31E-05	8.44E-05	1.87E-04	2.34E-04	2.94E-04	3.54E-04	4.89E-04	4.94E-04	6.05E-04	8.92E-04	9.98E-04	1.26E-03
8	C	4	$10,000,000.00	1.08E-05	4.69E-05	1.02E-04	1.17E-04	1.26E-04	1.65E-04	2.30E-04	2.34E-04	2.59E-04	3.49E-04	3.59E-04	4.65E-04
9	B	2	$100,000.00	3.80E-04	6.61E-04	1.28E-03	1.37E-03	1.65E-03	1.68E-03	2.01E-03	2.30E-03	2.58E-03	3.03E-03	3.48E-03	3.62E-03
10	C	4	$10,000,000.00	9.50E-05	3.67E-04	6.98E-04	6.87E-04	7.08E-04	7.83E-04	9.48E-04	1.09E-03	1.10E-03	1.18E-03	1.25E-03	1.34E-03
11	A	1	$10,000.00	3.17E-03	6.54E-03	5.57E-03	6.37E-03	7.75E-03	8.01E-03	8.72E-03	1.03E-02	1.03E-02	9.69E-03	9.72E-03	1.03E-02
12	A	1	$10,000.00	4.84E-04	1.77E-03	2.00E-03	2.35E-03	3.15E-03	3.36E-03	3.89E-03	5.01E-03	5.04E-03	4.65E-03	4.82E-03	5.01E-03
13	B	2	$100,000.00	9.69E-05	4.26E-04	6.46E-04	9.80E-04	1.66E-03	2.29E-03	3.31E-03	4.25E-03	5.29E-03	5.85E-03	6.64E-03	7.77E-03
14	C	4	$10,000,000.00	2.42E-05	2.37E-04	3.52E-04	4.90E-04	7.10E-04	1.07E-03	1.56E-03	2.01E-03	2.27E-03	2.29E-03	2.39E-03	2.88E-03
15	A	1	$10,000.00	5.38E-05	1.94E-04	2.41E-04	2.81E-04	3.73E-04	3.89E-04	4.86E-04	6.26E-04	6.17E-04	6.65E-04	6.81E-04	8.10E-04
16	B	2	$100,000.00	1.08E-05	4.68E-05	7.80E-05	1.17E-04	1.96E-04	2.66E-04	4.14E-04	5.31E-04	6.48E-04	8.36E-04	9.39E-04	1.26E-03
17	C	4	$10,000,000.00	2.69E-06	2.60E-05	4.26E-05	5.86E-05	8.40E-05	1.24E-04	1.95E-04	2.52E-04	2.78E-04	3.27E-04	3.38E-04	4.65E-04
18	B	2	$100,000.00	9.50E-05	3.67E-04	5.32E-04	6.86E-04	1.10E-03	1.26E-03	1.70E-03	2.48E-03	2.76E-03	2.84E-03	3.27E-03	3.62E-03
19	C	4	$10,000,000.00	2.37E-05	2.04E-04	2.90E-04	3.43E-04	4.71E-04	5.87E-04	8.01E-04	1.17E-03	1.18E-03	1.11E-03	1.18E-03	1.34E-03
20	A	1	$10,000.00	2.07E-06	4.48E-06	3.81E-06	4.36E-06	5.30E-06	5.60E-06	6.37E-06	7.86E-06	7.87E-06	7.38E-06	7.58E-06	8.34E-06
21	A	1	$10,000.00	3.17E-07	1.21E-06	1.37E-06	1.61E-06	2.16E-06	2.35E-06	2.84E-06	3.82E-06	3.84E-06	3.55E-06	3.75E-06	4.06E-06
22	B	2	$100,000.00	6.35E-08	2.92E-07	4.42E-07	6.70E-07	1.13E-06	1.60E-06	2.42E-06	3.24E-06	4.03E-06	4.46E-06	5.17E-06	6.30E-06
23	C	4	$10,000,000.00	1.59E-08	1.62E-07	2.41E-07	3.35E-07	4.85E-07	7.47E-07	1.14E-06	1.53E-06	1.73E-06	1.75E-06	1.86E-06	2.33E-06
24	A	1	$10,000.00	3.53E-08	1.33E-07	1.65E-07	1.92E-07	2.55E-07	2.72E-07	3.55E-07	4.77E-07	4.70E-07	5.06E-07	5.31E-07	6.57E-07
25	B	2	$100,000.00	7.05E-09	3.21E-08	5.34E-08	8.01E-08	1.34E-07	1.85E-07	3.02E-07	4.05E-07	4.94E-07	6.37E-07	7.32E-07	1.02E-06
26	C	4	$10,000,000.00	1.76E-09	1.78E-08	2.91E-08	4.01E-08	5.74E-08	8.65E-08	1.42E-07	1.92E-07	2.12E-07	2.49E-07	2.63E-07	3.77E-07
27	B	2	$100,000.00	6.22E-08	2.51E-07	3.64E-07	4.70E-07	7.52E-07	8.78E-07	1.24E-06	1.89E-06	2.10E-06	2.16E-06	2.55E-06	2.93E-06

End-State	Class	Severity	Dollar value	Prior Frequency	Posterior Frequency										
				0	1	2	3	4	5	6	7	8	9	10	11
28	C	4	$10,000,000.00	1.56E-08	1.40E-07	1.99E-07	2.35E-07	3.22E-07	4.10E-07	5.85E-07	8.95E-07	9.01E-07	8.46E-07	9.17E-07	1.09E-06
29	A	1	$10,000.00	4.17E-08	1.10E-07	9.37E-08	1.07E-07	1.30E-07	1.50E-07	1.84E-07	2.45E-07	2.45E-07	2.30E-07	2.35E-07	2.96E-07
30	A	1	$10,000.00	6.38E-09	2.97E-08	3.36E-08	3.95E-08	5.30E-08	6.29E-08	8.23E-08	1.19E-07	1.19E-07	1.10E-07	1.17E-07	1.44E-07
31	B	2	$100,000.00	1.28E-09	7.17E-09	1.09E-08	1.65E-08	2.78E-08	4.29E-08	7.00E-08	1.01E-07	1.25E-07	1.39E-07	1.61E-07	2.23E-07
32	C	4	$10,000,000.00	3.19E-10	3.98E-09	5.92E-09	8.23E-09	1.19E-08	2.00E-08	3.29E-08	4.77E-08	5.38E-08	5.43E-08	5.78E-08	8.28E-08
33	A	1	$10,000.00	7.09E-10	3.27E-09	4.06E-09	4.72E-09	6.27E-09	7.29E-09	1.03E-08	1.49E-08	1.46E-08	1.58E-08	1.65E-08	2.33E-08
34	B	2	$100,000.00	1.42E-10	7.88E-10	1.31E-09	1.97E-09	3.29E-09	4.97E-09	8.75E-09	1.26E-08	1.54E-08	1.98E-08	2.27E-08	3.61E-08
35	C	4	$10,000,000.00	3.54E-11	4.38E-10	7.16E-10	9.84E-10	1.41E-09	2.32E-09	4.12E-09	5.97E-09	6.58E-09	7.76E-09	8.18E-09	1.34E-08
36	B	2	$100,000.00	1.25E-09	6.17E-09	8.95E-09	1.15E-08	1.85E-08	2.35E-08	3.60E-08	5.88E-08	6.54E-08	6.72E-08	7.91E-08	1.04E-07
37	C	4	$10,000,000.00	3.13E-10	3.43E-09	4.88E-09	5.77E-09	7.92E-09	1.10E-08	1.70E-08	2.79E-08	2.80E-08	2.63E-08	2.85E-08	3.86E-08
38	C	4	$10,000,000.00	7.78E-10	2.49E-09	2.47E-09	2.96E-09	3.92E-09	4.90E-09	6.72E-09	9.63E-09	1.03E-08	1.02E-08	1.10E-08	1.48E-08
39	B	2	$100,000.00	1.27E-11	3.59E-11	3.59E-11	4.43E-11	6.17E-11	7.50E-11	1.03E-10	1.60E-10	1.76E-10	1.80E-10	1.99E-10	2.86E-10
40	C	4	$10,000,000.00	3.18E-12	1.99E-11	1.96E-11	2.21E-11	2.64E-11	3.50E-11	4.83E-11	7.58E-11	7.54E-11	7.03E-11	7.16E-11	1.06E-10
41	A	1	$10,000.00	7.50E-03	8.03E-03	7.96E-03	7.94E-03	8.58E-03	9.56E-03	1.02E-02	1.07E-02	1.14E-02	1.24E-02	1.35E-02	1.50E-02
42	A	1	$10,000.00	9.79E-05	9.83E-05	1.11E-04	1.06E-04	1.05E-04	1.08E-04	1.11E-04	1.10E-04	1.18E-04	1.39E-04	1.52E-04	1.69E-04
43	A	1	$10,000.00	1.50E-05	2.66E-05	3.99E-05	3.91E-05	4.28E-05	4.53E-05	4.97E-05	5.36E-05	5.75E-05	6.67E-05	7.55E-05	8.24E-05
44	B	2	$100,000.00	3.00E-06	6.41E-06	1.29E-05	1.63E-05	2.25E-05	3.09E-05	4.23E-05	4.54E-05	6.04E-05	8.39E-05	1.04E-04	1.28E-04
45	C	4	$10,000,000.00	7.49E-07	3.56E-06	7.04E-06	8.15E-06	9.63E-06	1.44E-05	1.99E-05	2.15E-05	2.59E-05	3.28E-05	3.75E-05	4.73E-05
46	A	1	$10,000.00	1.66E-06	2.92E-06	4.82E-06	4.68E-06	5.06E-06	5.25E-06	6.22E-06	6.69E-06	7.04E-06	9.53E-06	1.07E-05	1.33E-05
47	B	2	$100,000.00	3.33E-07	7.04E-07	1.56E-06	1.95E-06	2.66E-06	3.58E-06	5.28E-06	5.68E-06	7.40E-06	1.20E-05	1.47E-05	2.07E-05
48	C	4	$10,000,000.00	8.32E-08	3.91E-07	8.51E-07	9.75E-07	1.14E-06	1.67E-06	2.49E-06	2.69E-06	3.17E-06	4.69E-06	5.30E-06	7.65E-06
49	B	2	$100,000.00	2.94E-06	5.52E-06	1.06E-05	1.14E-05	1.49E-05	1.69E-05	2.18E-05	2.65E-05	3.15E-05	4.07E-05	5.13E-05	5.95E-05
50	C	4	$10,000,000.00	7.34E-07	3.06E-06	5.81E-06	5.71E-06	6.40E-06	7.91E-06	1.02E-05	1.26E-05	1.35E-05	1.59E-05	1.85E-05	2.21E-05
51	A	1	$10,000.00	2.45E-05	5.46E-05	4.64E-05	5.30E-05	7.00E-05	8.10E-05	9.42E-05	1.19E-04	1.26E-04	1.30E-04	1.43E-04	1.69E-04
52	A	1	$10,000.00	3.74E-06	1.48E-05	1.66E-05	1.96E-05	2.85E-05	3.40E-05	4.20E-05	5.76E-05	6.16E-05	6.25E-05	7.10E-05	8.24E-05
53	B	2	$100,000.00	7.49E-07	3.56E-06	5.37E-06	8.15E-06	1.50E-05	2.32E-05	3.57E-05	4.89E-05	6.47E-05	7.86E-05	9.79E-05	1.28E-04
54	C	4	$10,000,000.00	1.87E-07	1.98E-06	2.93E-06	4.07E-06	6.42E-06	1.08E-05	1.68E-05	2.32E-05	2.77E-05	3.08E-05	3.52E-05	4.73E-05

End-State	Class	Severity	Dollar value	Prior Frequency	Posterior Frequency										
				0	1	2	3	4	5	6	7	8	9	10	11
55	A	1	$10,000.00	4.16E-07	1.62E-06	2.01E-06	2.34E-06	3.37E-06	3.93E-06	5.26E-06	7.20E-06	7.54E-06	8.93E-06	1.00E-05	1.33E-05
56	B	2	$100,000.00	8.32E-08	3.91E-07	6.50E-07	9.74E-07	1.77E-06	2.68E-06	4.47E-06	6.11E-06	7.92E-06	1.12E-05	1.38E-05	2.06E-05
57	C	4	$10,000,000.00	2.08E-08	2.17E-07	3.54E-07	4.87E-07	7.59E-07	1.25E-06	2.10E-06	2.89E-06	3.39E-06	4.40E-06	4.98E-06	7.64E-06
58	B	2	$100,000.00	7.34E-07	3.06E-06	4.43E-06	5.71E-06	9.94E-06	1.27E-05	1.84E-05	2.85E-05	3.37E-05	3.81E-05	4.82E-05	5.95E-05
59	C	4	$10,000,000.00	1.83E-07	1.70E-06	2.42E-06	2.85E-06	4.26E-06	5.93E-06	8.66E-06	1.35E-05	1.45E-05	1.49E-05	1.74E-05	2.20E-05
60	A	1	$10,000.00	1.60E-08	3.74E-08	3.17E-08	3.62E-08	4.79E-08	5.65E-08	6.88E-08	9.05E-08	9.62E-08	9.92E-08	1.12E-07	1.37E-07
61	A	1	$10,000.00	2.45E-09	1.01E-08	1.14E-08	1.34E-08	1.95E-08	2.37E-08	3.07E-08	4.39E-08	4.69E-08	4.76E-08	5.53E-08	6.68E-08
62	B	2	$100,000.00	4.91E-10	2.44E-09	3.68E-09	5.57E-09	1.02E-08	1.62E-08	2.61E-08	3.73E-08	4.93E-08	5.99E-08	7.63E-08	1.04E-07
63	C	4	$10,000,000.00	1.23E-10	1.35E-09	2.01E-09	2.79E-09	4.39E-09	7.55E-09	1.23E-08	1.77E-08	2.11E-08	2.34E-08	2.75E-08	3.84E-08
64	A	1	$10,000.00	2.73E-10	1.11E-09	1.37E-09	1.60E-09	2.31E-09	2.75E-09	3.84E-09	5.49E-09	5.75E-09	6.81E-09	7.83E-09	1.08E-08
65	B	2	$100,000.00	5.45E-11	2.68E-10	4.45E-10	6.67E-10	1.21E-09	1.87E-09	3.26E-09	4.66E-09	6.03E-09	8.56E-09	1.08E-08	1.67E-08
66	C	4	$10,000,000.00	1.36E-11	1.49E-10	2.43E-10	3.33E-10	5.19E-10	8.74E-10	1.54E-09	2.21E-09	2.59E-09	3.35E-09	3.88E-09	6.20E-09
67	B	2	$100,000.00	4.81E-10	2.10E-09	3.03E-09	3.91E-09	6.80E-09	8.87E-09	1.34E-08	2.17E-08	2.57E-08	2.90E-08	3.76E-08	4.82E-08
68	C	4	$10,000,000.00	1.20E-10	1.16E-09	1.66E-09	1.95E-09	2.91E-09	4.14E-09	6.32E-09	1.03E-08	1.10E-08	1.14E-08	1.35E-08	1.79E-08
69	A	1	$10,000.00	3.22E-10	9.18E-10	7.80E-10	8.90E-10	1.18E-09	1.52E-09	1.99E-09	2.82E-09	2.99E-09	3.09E-09	3.47E-09	4.86E-09
70	A	1	$10,000.00	4.93E-11	2.48E-10	2.79E-10	3.29E-10	4.79E-10	6.36E-10	8.89E-10	1.37E-09	1.46E-09	1.48E-09	1.72E-09	2.37E-09
71	B	2	$100,000.00	9.86E-12	5.98E-11	9.04E-11	1.37E-10	2.51E-10	4.34E-10	7.56E-10	1.16E-09	1.53E-09	1.86E-09	2.37E-09	3.67E-09
72	C	4	$10,000,000.00	2.47E-12	3.32E-11	4.93E-11	6.85E-11	1.08E-10	2.02E-10	3.56E-10	5.49E-10	6.57E-10	7.30E-10	8.53E-10	1.36E-09
73	A	1	$10,000.00	5.48E-12	2.73E-11	3.38E-11	3.93E-11	5.66E-11	7.36E-11	1.11E-10	1.71E-10	1.79E-10	2.12E-10	2.43E-10	3.83E-10
74	B	2	$100,000.00	1.10E-12	6.57E-12	1.09E-11	1.64E-11	2.97E-11	5.02E-11	9.45E-11	1.45E-10	1.88E-10	2.66E-10	3.35E-10	5.94E-10
75	C	4	$10,000,000.00	2.74E-13	3.65E-12	5.96E-12	8.19E-12	1.27E-11	2.34E-11	4.45E-11	6.87E-11	8.05E-11	1.04E-10	1.21E-10	2.20E-10
76	B	2	$100,000.00	9.67E-12	5.15E-11	7.45E-11	9.60E-11	1.67E-10	2.38E-10	3.89E-10	6.77E-10	8.00E-10	9.04E-10	1.17E-09	1.71E-09
77	C	4	$10,000,000.00	2.42E-12	2.86E-11	4.07E-11	4.80E-11	7.16E-11	1.11E-10	1.83E-10	3.20E-10	3.43E-10	3.54E-10	4.20E-10	6.34E-10
78	C	4	$10,000,000.00	6.01E-12	2.08E-11	2.06E-11	2.46E-11	3.55E-11	4.95E-11	7.26E-11	1.11E-10	1.25E-10	1.37E-10	1.63E-10	2.43E-10
79	B	2	$100,000.00	9.82E-14	2.99E-13	2.99E-13	3.68E-13	5.57E-13	7.57E-13	1.11E-12	1.84E-12	2.15E-12	2.41E-12	2.93E-12	4.71E-12
80	C	4	$10,000,000.00	2.45E-14	1.66E-13	1.63E-13	1.84E-13	2.39E-13	3.53E-13	5.21E-13	8.72E-13	9.21E-13	9.44E-13	1.06E-12	1.74E-12
81	A	1	$10,000.00	8.33E-04	9.81E-04	9.73E-04	9.70E-04	1.04E-03	1.16E-03	1.21E-03	1.27E-03	1.33E-03	1.44E-03	1.69E-03	2.34E-03

End-State	Class	Severity	Dollar value	Prior Frequency	Posterior Frequency										
				0	1	2	3	4	5	6	7	8	9	10	11
82	A	1	$10,000.00	1.09E-05	1.20E-05	1.36E-05	1.30E-05	1.27E-05	1.31E-05	1.33E-05	1.30E-05	1.38E-05	1.61E-05	1.91E-05	2.64E-05
83	A	1	$10,000.00	1.66E-06	3.25E-06	4.88E-06	4.78E-06	5.17E-06	5.48E-06	5.95E-06	6.33E-06	6.73E-06	7.73E-06	9.44E-06	1.29E-05
84	B	2	$100,000.00	3.33E-07	7.83E-07	1.58E-06	1.99E-06	2.72E-06	3.74E-06	5.05E-06	5.37E-06	7.07E-06	9.72E-06	1.30E-05	2.00E-05
85	C	4	$10,000,000.00	8.32E-08	4.35E-07	8.60E-07	9.96E-07	1.16E-06	1.74E-06	2.38E-06	2.55E-06	3.03E-06	3.80E-06	4.69E-06	7.40E-06
86	A	1	$10,000.00	1.85E-07	3.57E-07	5.89E-07	5.72E-07	6.12E-07	6.35E-07	7.43E-07	7.92E-07	8.24E-07	1.10E-06	1.33E-06	2.08E-06
87	B	2	$100,000.00	3.70E-08	8.61E-08	1.91E-07	2.38E-07	3.21E-07	4.33E-07	6.32E-07	6.72E-07	8.66E-07	1.39E-06	1.84E-06	3.23E-06
88	C	4	$10,000,000.00	9.25E-09	4.78E-08	1.04E-07	1.19E-07	1.38E-07	2.02E-07	2.97E-07	3.18E-07	3.71E-07	5.43E-07	6.63E-07	1.20E-06
89	B	2	$100,000.00	3.26E-07	6.74E-07	1.30E-06	1.40E-06	1.80E-06	2.05E-06	2.60E-06	3.14E-06	3.69E-06	4.71E-06	6.41E-06	9.30E-06
90	C	4	$10,000,000.00	8.16E-08	3.75E-07	7.10E-07	6.98E-07	7.73E-07	9.56E-07	1.22E-06	1.49E-06	1.58E-06	1.84E-06	2.31E-06	3.45E-06
91	A	1	$10,000.00	2.72E-06	6.67E-06	5.67E-06	6.47E-06	8.46E-06	9.79E-06	1.13E-05	1.40E-05	1.48E-05	1.51E-05	1.79E-05	2.64E-05
92	A	1	$10,000.00	4.16E-07	1.80E-06	2.03E-06	2.39E-06	3.45E-06	4.11E-06	5.03E-06	6.82E-06	7.21E-06	7.24E-06	8.88E-06	1.29E-05
93	B	2	$100,000.00	8.32E-08	4.35E-07	6.57E-07	9.96E-07	1.81E-06	2.80E-06	4.27E-06	5.78E-06	7.57E-06	9.10E-06	1.22E-05	2.00E-05
94	C	4	$10,000,000.00	2.08E-08	2.42E-07	3.58E-07	4.98E-07	7.76E-07	1.31E-06	2.01E-06	2.74E-06	3.24E-06	3.56E-06	4.41E-06	7.39E-06
95	A	1	$10,000.00	4.62E-08	1.98E-07	2.45E-07	2.86E-07	4.08E-07	4.76E-07	6.28E-07	8.52E-07	8.83E-07	1.03E-06	1.26E-06	2.08E-06
96	B	2	$100,000.00	9.24E-09	4.78E-08	7.94E-08	1.19E-07	2.14E-07	3.24E-07	5.34E-07	7.23E-07	9.27E-07	1.30E-06	1.73E-06	3.22E-06
97	C	4	$10,000,000.00	2.31E-09	2.65E-08	4.33E-08	5.95E-08	9.17E-08	1.51E-07	2.51E-07	3.42E-07	3.97E-07	5.09E-07	6.23E-07	1.19E-06
98	B	2	$100,000.00	8.15E-08	3.74E-07	5.42E-07	6.98E-07	1.20E-06	1.53E-06	2.20E-06	3.37E-06	3.95E-06	4.41E-06	6.02E-06	9.30E-06
99	C	4	$10,000,000.00	2.04E-08	2.08E-07	2.96E-07	3.49E-07	5.15E-07	7.16E-07	1.04E-06	1.60E-06	1.69E-06	1.73E-06	2.17E-06	3.44E-06
100	A	1	$10,000.00	1.78E-09	4.57E-09	3.88E-09	4.43E-09	5.79E-09	6.83E-09	8.23E-09	1.07E-08	1.13E-08	1.15E-08	1.40E-08	2.14E-08
101	A	1	$10,000.00	2.73E-10	1.23E-09	1.39E-09	1.64E-09	2.36E-09	2.87E-09	3.67E-09	5.20E-09	5.49E-09	5.52E-09	6.92E-09	1.04E-08
102	B	2	$100,000.00	5.45E-11	2.98E-10	4.50E-10	6.81E-10	1.24E-09	1.96E-09	3.12E-09	4.41E-09	5.77E-09	6.94E-09	9.54E-09	1.62E-08
103	C	4	$10,000,000.00	1.36E-11	1.65E-10	2.45E-10	3.41E-10	5.30E-10	9.13E-10	1.47E-09	2.09E-09	2.47E-09	2.71E-09	3.43E-09	5.99E-09
104	A	1	$10,000.00	3.03E-11	1.36E-10	1.68E-10	1.96E-10	2.79E-10	3.32E-10	4.59E-10	6.50E-10	6.73E-10	7.88E-10	9.78E-10	1.69E-09
105	B	2	$100,000.00	6.06E-12	3.27E-11	5.44E-11	8.15E-11	1.46E-10	2.26E-10	3.90E-10	5.51E-10	7.06E-10	9.91E-10	1.35E-09	2.61E-09
106	C	4	$10,000,000.00	1.51E-12	1.82E-11	2.96E-11	4.07E-11	6.27E-11	1.06E-10	1.84E-10	2.61E-10	3.03E-10	3.88E-10	4.86E-10	9.68E-10
107	B	2	$100,000.00	5.34E-11	2.56E-10	3.71E-10	4.77E-10	8.22E-10	1.07E-09	1.61E-09	2.57E-09	3.01E-09	3.36E-09	4.70E-09	7.54E-09
108	C	4	$10,000,000.00	1.34E-11	1.42E-10	2.02E-10	2.39E-10	3.52E-10	5.00E-10	7.56E-10	1.22E-09	1.29E-09	1.32E-09	1.69E-09	2.79E-09

End-State	Class	Severity	Dollar value	Prior Frequency	Posterior Frequency										
				0	1	2	3	4	5	6	7	8	9	10	11
109	**A**	1	$10,000.00	3.58E-11	1.12E-10	9.53E-11	1.09E-10	1.42E-10	1.83E-10	2.38E-10	3.33E-10	3.50E-10	3.57E-10	4.34E-10	7.60E-10
110	**A**	1	$10,000.00	5.48E-12	3.03E-11	3.41E-11	4.02E-11	5.79E-11	7.69E-11	1.06E-10	1.62E-10	1.71E-10	1.72E-10	2.15E-10	3.70E-10
111	**B**	2	$100,000.00	1.10E-12	7.31E-12	1.10E-11	1.67E-11	3.04E-11	5.24E-11	9.04E-11	1.37E-10	1.79E-10	2.16E-10	2.96E-10	5.74E-10
112	**C**	4	$10,000,000.00	2.74E-13	4.06E-12	6.02E-12	8.37E-12	1.30E-11	2.45E-11	4.25E-11	6.50E-11	7.69E-11	8.45E-11	1.07E-10	2.13E-10
113	**A**	1	$10,000.00	6.09E-13	3.33E-12	4.13E-12	4.80E-12	6.85E-12	8.90E-12	1.33E-11	2.02E-11	2.09E-11	2.45E-11	3.04E-11	5.98E-11
114	**B**	2	$100,000.00	1.22E-13	8.03E-13	1.34E-12	2.00E-12	3.59E-12	6.07E-12	1.13E-11	1.71E-11	2.20E-11	3.08E-11	4.19E-11	9.28E-11
115	**C**	4	$10,000,000.00	3.04E-14	4.46E-13	7.28E-13	1.00E-12	1.54E-12	2.83E-12	5.32E-12	8.12E-12	9.42E-12	1.21E-11	1.51E-11	3.44E-11
116	**B**	2	$100,000.00	1.07E-12	6.29E-12	9.11E-12	1.17E-11	2.02E-11	2.87E-11	4.65E-11	8.00E-11	9.36E-11	1.05E-10	1.46E-10	2.67E-10
117	**C**	4	$10,000,000.00	2.69E-13	3.50E-12	4.97E-12	5.86E-12	8.65E-12	1.34E-11	2.19E-11	3.79E-11	4.01E-11	4.09E-11	5.25E-11	9.90E-11
118	**C**	4	$10,000,000.00	6.68E-13	2.54E-12	2.51E-12	3.01E-12	4.29E-12	5.98E-12	8.68E-12	1.31E-11	1.47E-11	1.59E-11	2.04E-11	3.80E-11
119	**B**	2	$100,000.00	1.09E-14	3.66E-14	3.65E-14	4.50E-14	6.74E-14	9.16E-14	1.32E-13	2.18E-13	2.52E-13	2.79E-13	3.67E-13	7.36E-13
120	**C**	4	$10,000,000.00	2.73E-15	2.03E-14	1.99E-14	2.25E-14	2.89E-14	4.27E-14	6.23E-14	1.03E-13	1.08E-13	1.09E-13	1.32E-13	2.72E-13
121	**A**	1	$10,000.00	1.25E-03	1.33E-03	1.31E-03	1.31E-03	1.39E-03	1.86E-03	1.94E-03	2.01E-03	2.09E-03	2.45E-03	2.61E-03	2.82E-03
122	**A**	1	$10,000.00	1.63E-05	1.62E-05	1.84E-05	1.75E-05	1.70E-05	2.11E-05	2.13E-05	2.07E-05	2.17E-05	2.75E-05	2.93E-05	3.19E-05
123	**A**	1	$10,000.00	2.50E-06	4.39E-06	6.59E-06	6.46E-06	6.92E-06	8.85E-06	9.51E-06	1.00E-05	1.06E-05	1.32E-05	1.45E-05	1.55E-05
124	**B**	2	$100,000.00	4.99E-07	1.06E-06	2.13E-06	2.69E-06	3.64E-06	6.03E-06	8.08E-06	8.52E-06	1.11E-05	1.66E-05	2.00E-05	2.41E-05
125	**C**	4	$10,000,000.00	1.25E-07	5.88E-07	1.16E-06	1.35E-06	1.56E-06	2.81E-06	3.80E-06	4.04E-06	4.76E-06	6.49E-06	7.22E-06	8.91E-06
126	**A**	1	$10,000.00	2.77E-07	4.82E-07	7.96E-07	7.72E-07	8.19E-07	1.02E-06	1.19E-06	1.26E-06	1.30E-06	1.88E-06	2.06E-06	2.51E-06
127	**B**	2	$100,000.00	5.55E-08	1.16E-07	2.58E-07	3.22E-07	4.30E-07	6.98E-07	1.01E-06	1.07E-06	1.36E-06	2.37E-06	2.83E-06	3.89E-06
128	**C**	4	$10,000,000.00	1.39E-08	6.46E-08	1.40E-07	1.61E-07	1.84E-07	3.26E-07	4.76E-07	5.05E-07	5.83E-07	9.27E-07	1.02E-06	1.44E-06
129	**B**	2	$100,000.00	4.90E-07	9.11E-07	1.76E-06	1.89E-06	2.41E-06	3.31E-06	4.16E-06	4.97E-06	5.80E-06	8.04E-06	9.87E-06	1.12E-05
130	**C**	4	$10,000,000.00	1.22E-07	5.06E-07	9.59E-07	9.43E-07	1.03E-06	1.54E-06	1.96E-06	2.36E-06	2.48E-06	3.15E-06	3.55E-06	4.15E-06
131	**A**	1	$10,000.00	4.08E-06	9.01E-06	7.66E-06	8.74E-06	1.13E-05	1.58E-05	1.80E-05	2.23E-05	2.32E-05	2.57E-05	2.76E-05	3.18E-05
132	**A**	1	$10,000.00	6.24E-07	2.44E-06	2.74E-06	3.23E-06	4.61E-06	6.63E-06	8.04E-06	1.08E-05	1.13E-05	1.24E-05	1.37E-05	1.55E-05
133	**B**	2	$100,000.00	1.25E-07	5.87E-07	8.87E-07	1.35E-06	2.42E-06	4.52E-06	6.84E-06	9.17E-06	1.19E-05	1.55E-05	1.88E-05	2.40E-05
134	**C**	4	$10,000,000.00	3.12E-08	3.26E-07	4.84E-07	6.73E-07	1.04E-06	2.11E-06	3.22E-06	4.34E-06	5.10E-06	6.08E-06	6.79E-06	8.90E-06
135	**A**	1	$10,000.00	6.93E-08	2.68E-07	3.31E-07	3.86E-07	5.46E-07	7.68E-07	1.01E-06	1.35E-06	1.39E-06	1.76E-06	1.93E-06	2.51E-06

End-State	Class	Severity	Dollar value	Prior Frequency	Posterior Frequency										
				0	1	2	3	4	5	6	7	8	9	10	11
136	B	2	$100,000.00	1.39E-08	6.45E-08	1.07E-07	1.61E-07	2.86E-07	5.23E-07	8.54E-07	1.15E-06	1.46E-06	2.22E-06	2.67E-06	3.89E-06
137	C	4	$10,000,000.00	3.47E-09	3.59E-08	5.85E-08	8.04E-08	1.23E-07	2.44E-07	4.02E-07	5.43E-07	6.25E-07	8.69E-07	9.60E-07	1.44E-06
138	B	2	$100,000.00	1.22E-07	5.06E-07	7.32E-07	9.43E-07	1.61E-06	2.48E-06	3.52E-06	5.35E-06	6.20E-06	7.53E-06	9.28E-06	1.12E-05
139	C	4	$10,000,000.00	3.06E-08	2.81E-07	3.99E-07	4.71E-07	6.89E-07	1.16E-06	1.66E-06	2.53E-06	2.66E-06	2.95E-06	3.34E-06	4.15E-06
140	A	1	$10,000.00	2.67E-09	6.17E-09	5.24E-09	5.98E-09	7.74E-09	1.10E-08	1.32E-08	1.70E-08	1.77E-08	1.96E-08	2.15E-08	2.58E-08
141	A	1	$10,000.00	4.09E-10	1.67E-09	1.88E-09	2.21E-09	3.15E-09	4.63E-09	5.87E-09	8.24E-09	8.64E-09	9.41E-09	1.07E-08	1.26E-08
142	B	2	$100,000.00	8.18E-11	4.02E-10	6.07E-10	9.20E-10	1.66E-09	3.16E-09	4.99E-09	6.99E-09	9.07E-09	1.18E-08	1.47E-08	1.95E-08
143	C	4	$10,000,000.00	2.04E-11	2.23E-10	3.31E-10	4.60E-10	7.10E-10	1.47E-09	2.35E-09	3.31E-09	3.89E-09	4.63E-09	5.29E-09	7.22E-09
144	A	1	$10,000.00	4.54E-11	1.83E-10	2.27E-10	2.64E-10	3.73E-10	5.36E-10	7.34E-10	1.03E-09	1.06E-09	1.34E-09	1.51E-09	2.03E-09
145	B	2	$100,000.00	9.08E-12	4.42E-11	7.34E-11	1.10E-10	1.96E-10	3.66E-10	6.24E-10	8.74E-10	1.11E-09	1.69E-09	2.08E-09	3.15E-09
146	C	4	$10,000,000.00	2.27E-12	2.45E-11	4.00E-11	5.50E-11	8.39E-11	1.71E-10	2.94E-10	4.14E-10	4.76E-10	6.62E-10	7.48E-10	1.17E-09
147	B	2	$100,000.00	8.02E-11	3.46E-10	5.01E-10	6.45E-10	1.10E-09	1.73E-09	2.57E-09	4.08E-09	4.73E-09	5.74E-09	7.23E-09	9.08E-09
148	C	4	$10,000,000.00	2.00E-11	1.92E-10	2.73E-10	3.22E-10	4.71E-10	8.07E-10	1.21E-09	1.93E-09	2.03E-09	2.25E-09	2.60E-09	3.36E-09
149	A	1	$10,000.00	5.37E-11	1.51E-10	1.29E-10	1.47E-10	1.90E-10	2.96E-10	3.81E-10	5.28E-10	5.51E-10	6.10E-10	6.68E-10	9.16E-10
150	A	1	$10,000.00	8.22E-12	4.10E-11	4.61E-11	5.43E-11	7.75E-11	1.24E-10	1.70E-10	2.56E-10	2.69E-10	2.93E-10	3.31E-10	4.46E-10
151	B	2	$100,000.00	1.64E-12	9.88E-12	1.49E-11	2.26E-11	4.07E-11	8.46E-11	1.45E-10	2.18E-10	2.82E-10	3.68E-10	4.56E-10	6.92E-10
152	C	4	$10,000,000.00	4.11E-13	5.49E-12	8.14E-12	1.13E-11	1.74E-11	3.95E-11	6.80E-11	1.03E-10	1.21E-10	1.44E-10	1.64E-10	2.56E-10
153	A	1	$10,000.00	9.13E-13	4.50E-12	5.57E-12	6.49E-12	9.16E-12	1.44E-11	2.13E-11	3.21E-11	3.29E-11	4.18E-11	4.68E-11	7.21E-11
154	B	2	$100,000.00	1.83E-13	1.09E-12	1.80E-12	2.70E-12	4.81E-12	9.80E-12	1.81E-11	2.72E-11	3.46E-11	5.26E-11	6.45E-11	1.12E-10
155	C	4	$10,000,000.00	4.57E-14	6.03E-13	9.84E-13	1.35E-12	2.06E-12	4.57E-12	8.50E-12	1.29E-11	1.48E-11	2.06E-11	2.32E-11	4.14E-11
156	B	2	$100,000.00	1.61E-12	8.50E-12	1.23E-11	1.58E-11	2.70E-11	4.64E-11	7.44E-11	1.27E-10	1.47E-10	1.79E-10	2.24E-10	3.22E-10
157	C	4	$10,000,000.00	4.03E-13	4.72E-12	6.71E-12	7.92E-12	1.16E-11	2.16E-11	3.50E-11	6.01E-11	6.31E-11	6.99E-11	8.08E-11	1.19E-10
158	C	4	$10,000,000.00	1.00E-12	3.43E-12	3.40E-12	4.06E-12	5.74E-12	9.66E-12	1.39E-11	2.08E-11	2.31E-11	2.71E-11	3.13E-11	4.58E-11
159	B	2	$100,000.00	1.64E-14	4.94E-14	4.93E-14	6.08E-14	9.01E-14	1.48E-13	2.12E-13	3.45E-13	3.96E-13	4.77E-13	5.64E-13	8.86E-13
160	C	4	$10,000,000.00	4.09E-15	2.75E-14	2.69E-14	3.04E-14	3.86E-14	6.90E-14	9.97E-14	1.64E-13	1.70E-13	1.87E-13	2.03E-13	3.28E-13
161	A	1	$10,000.00	1.80E-04	1.60E-04	1.37E-04	1.31E-04	1.27E-04	1.72E-04	1.62E-04	1.58E-04	1.55E-04	1.69E-04	1.70E-04	1.76E-04
162	A	1	$10,000.00	2.75E-05	4.33E-05	4.91E-05	4.82E-05	5.19E-05	7.24E-05	7.23E-05	7.68E-05	7.54E-05	8.10E-05	8.43E-05	8.55E-05

End-State	Class	Severity	Dollar value	Prior Frequency	Posterior Frequency										
				0	1	2	3	4	5	6	7	8	9	10	11
163	B	2	$100,000.00	5.50E-06	1.04E-05	1.59E-05	2.01E-05	2.72E-05	4.94E-05	6.14E-05	6.51E-05	7.92E-05	1.02E-04	1.16E-04	1.33E-04
164	C	4	$10,000,000.00	1.38E-06	5.80E-06	8.66E-06	1.00E-05	1.17E-05	2.30E-05	2.89E-05	3.08E-05	3.39E-05	3.98E-05	4.18E-05	4.91E-05
165	A	1	$10,000.00	3.06E-06	4.76E-06	5.93E-06	5.77E-06	6.14E-06	8.38E-06	9.03E-06	9.60E-06	9.23E-06	1.16E-05	1.19E-05	1.38E-05
166	B	2	$100,000.00	6.12E-07	1.15E-06	1.92E-06	2.40E-06	3.22E-06	5.71E-06	7.68E-06	8.14E-06	9.70E-06	1.45E-05	1.64E-05	2.14E-05
167	C	4	$10,000,000.00	1.53E-07	6.38E-07	1.05E-06	1.20E-06	1.38E-06	2.67E-06	3.61E-06	3.86E-06	4.16E-06	5.69E-06	5.92E-06	7.94E-06
168	B	2	$100,000.00	5.40E-06	8.99E-06	1.31E-05	1.41E-05	1.81E-05	2.71E-05	3.16E-05	3.80E-05	4.13E-05	4.93E-05	5.72E-05	6.18E-05
169	C	4	$10,000,000.00	1.35E-06	5.00E-06	7.14E-06	7.04E-06	7.76E-06	1.26E-05	1.49E-05	1.80E-05	1.77E-05	1.93E-05	2.06E-05	2.29E-05
170	A	1	$10,000.00	1.18E-07	1.10E-07	9.38E-08	8.94E-08	8.71E-08	1.20E-07	1.18E-07	1.21E-07	1.18E-07	1.28E-07	1.33E-07	1.42E-07
171	A	1	$10,000.00	1.80E-08	2.97E-08	3.36E-08	3.30E-08	3.55E-08	5.06E-08	5.28E-08	5.85E-08	5.75E-08	6.17E-08	6.57E-08	6.93E-08
172	B	2	$100,000.00	3.61E-09	7.15E-09	1.09E-08	1.38E-08	1.86E-08	3.45E-08	4.49E-08	4.96E-08	6.03E-08	7.76E-08	9.06E-08	1.07E-07
173	C	4	$10,000,000.00	9.02E-10	3.97E-09	5.93E-09	6.88E-09	7.98E-09	1.61E-08	2.11E-08	2.35E-08	2.59E-08	3.04E-08	3.26E-08	3.98E-08
174	A	1	$10,000.00	2.00E-09	3.26E-09	4.06E-09	3.95E-09	4.20E-09	5.85E-09	6.60E-09	7.32E-09	7.04E-09	8.81E-09	9.29E-09	1.12E-08
175	B	2	$100,000.00	4.01E-10	7.86E-10	1.31E-09	1.64E-09	2.20E-09	3.99E-09	5.61E-09	6.21E-09	7.39E-09	1.11E-08	1.28E-08	1.74E-08
176	C	4	$10,000,000.00	1.00E-10	4.37E-10	7.17E-10	8.22E-10	9.44E-10	1.86E-09	2.64E-09	2.94E-09	3.17E-09	4.34E-09	4.61E-09	6.43E-09
177	B	2	$100,000.00	3.54E-09	6.16E-09	8.96E-09	9.64E-09	1.24E-08	1.89E-08	2.31E-08	2.90E-08	3.15E-08	3.76E-08	4.46E-08	5.01E-08
178	C	4	$10,000,000.00	8.84E-10	3.42E-09	4.89E-09	4.82E-09	5.30E-09	8.82E-09	1.09E-08	1.37E-08	1.35E-08	1.47E-08	1.61E-08	1.85E-08
179	A	1	$10,000.00	2.37E-09	2.69E-09	2.30E-09	2.20E-09	2.14E-09	3.23E-09	3.43E-09	3.75E-09	3.67E-09	4.00E-09	4.12E-09	5.05E-09
180	A	1	$10,000.00	3.63E-10	7.29E-10	8.25E-10	8.11E-10	8.72E-10	1.35E-09	1.53E-09	1.82E-09	1.79E-09	1.92E-09	2.04E-09	2.46E-09
181	B	2	$100,000.00	7.25E-11	1.76E-10	2.67E-10	3.38E-10	4.58E-10	9.24E-10	1.30E-09	1.54E-09	1.88E-09	2.41E-09	2.81E-09	3.81E-09
182	C	4	$10,000,000.00	1.81E-11	9.76E-11	1.46E-10	1.69E-10	1.96E-10	4.31E-10	6.11E-10	7.32E-10	8.05E-10	9.45E-10	1.01E-09	1.41E-09
183	A	1	$10,000.00	4.03E-11	8.01E-11	9.97E-11	9.69E-11	1.03E-10	1.57E-10	1.91E-10	2.28E-10	2.19E-10	2.74E-10	2.89E-10	3.97E-10
184	B	2	$100,000.00	8.06E-12	1.93E-11	3.23E-11	4.04E-11	5.41E-11	1.07E-10	1.62E-10	1.93E-10	2.30E-10	3.45E-10	3.98E-10	6.16E-10
185	C	4	$10,000,000.00	2.01E-12	1.07E-11	1.76E-11	2.02E-11	2.32E-11	4.99E-11	7.64E-11	9.15E-11	9.85E-11	1.35E-10	1.43E-10	2.28E-10
186	B	2	$100,000.00	7.11E-11	1.51E-10	2.20E-10	2.37E-10	3.04E-10	5.06E-10	6.69E-10	9.01E-10	9.79E-10	1.17E-09	1.38E-09	1.78E-09
187	C	4	$10,000,000.00	1.78E-11	8.40E-11	1.20E-10	1.18E-10	1.30E-10	2.36E-10	3.15E-10	4.27E-10	4.20E-10	4.58E-10	4.98E-10	6.58E-10
188	C	4	$10,000,000.00	4.42E-11	6.09E-11	6.08E-11	6.07E-11	6.45E-11	1.05E-10	1.25E-10	1.48E-10	1.54E-10	1.78E-10	1.93E-10	2.52E-10
189	B	2	$100,000.00	7.22E-13	8.80E-13	8.83E-13	9.08E-13	1.01E-12	1.61E-12	1.90E-12	2.45E-12	2.63E-12	3.13E-12	3.48E-12	4.89E-12

End-State	Class	Severity	Dollar value	Prior Frequency	Posterior Frequency										
				0	1	2	3	4	5	6	7	8	9	10	11
190	C	4	$10,000,000.00	1.80E-13	4.89E-13	4.82E-13	4.54E-13	4.35E-13	7.53E-13	8.96E-13	1.16E-12	1.13E-12	1.22E-12	1.25E-12	1.81E-12

Table C-2. End-state probabilities for the ISOM unit over the 11 year period

End-State	Class	Severity	Dollar value	Prior Risk	Posterior Risk										
				0	1	2	3	4	5	6	7	8	9	10	11
1	A	1	$10,000.00	9.70E+03	9.62E+03	9.56E+03	9.54E+03	9.50E+03	9.46E+03	9.40E+03	9.33E+03	9.29E+03	9.24E+03	9.19E+03	9.11E+03
2	A	1	$10,000.00	1.27E+02	1.18E+02	1.34E+02	1.27E+02	1.16E+02	1.07E+02	1.03E+02	9.59E+01	9.65E+01	1.03E+02	1.03E+02	1.03E+02
3	A	1	$10,000.00	1.94E+01	3.18E+01	4.79E+01	4.71E+01	4.74E+01	4.49E+01	4.60E+01	4.65E+01	4.71E+01	4.97E+01	5.12E+01	5.01E+01
4	B	2	$100,000.00	3.88E+01	7.68E+01	1.55E+02	1.96E+02	2.49E+02	3.06E+02	3.91E+02	3.95E+02	4.94E+02	6.25E+02	7.06E+02	7.78E+02
5	C	4	$10,000,000.00	9.69E+02	4.26E+03	8.46E+03	9.80E+03	1.07E+04	1.43E+04	1.84E+04	1.87E+04	2.12E+04	2.44E+04	2.54E+04	2.88E+04
6	A	1	$10,000.00	2.15E+00	3.50E+00	5.79E+00	5.63E+00	5.60E+00	5.20E+00	5.75E+00	5.82E+00	5.76E+00	7.10E+00	7.24E+00	8.10E+00
7	B	2	$100,000.00	4.31E+00	8.44E+00	1.87E+01	2.34E+01	2.94E+01	3.54E+01	4.89E+01	4.94E+01	6.05E+01	8.92E+01	9.98E+01	1.26E+02
8	C	4	$10,000,000.00	1.08E+02	4.69E+02	1.02E+03	1.17E+03	1.26E+03	1.65E+03	2.30E+03	2.34E+03	2.59E+03	3.49E+03	3.59E+03	4.65E+03
9	B	2	$100,000.00	3.80E+01	6.61E+01	1.28E+02	1.37E+02	1.65E+02	1.68E+02	2.01E+02	2.30E+02	2.58E+02	3.03E+02	3.48E+02	3.62E+02
10	C	4	$10,000,000.00	9.50E+02	3.67E+03	6.98E+03	6.87E+03	7.08E+03	7.83E+03	9.48E+03	1.09E+04	1.10E+04	1.18E+04	1.25E+04	1.34E+04
11	A	1	$10,000.00	3.17E+01	6.54E+01	5.57E+01	6.37E+01	7.75E+01	8.01E+01	8.72E+01	1.03E+02	1.03E+02	9.69E+01	9.72E+01	1.03E+02
12	A	1	$10,000.00	4.84E+00	1.77E+01	2.00E+01	2.35E+01	3.15E+01	3.36E+01	3.89E+01	5.01E+01	5.04E+01	4.65E+01	4.82E+01	5.01E+01
13	B	2	$100,000.00	9.69E+00	4.26E+01	6.46E+01	9.80E+01	1.66E+02	2.29E+02	3.31E+02	4.25E+02	5.29E+02	5.85E+02	6.64E+02	7.77E+02
14	C	4	$10,000,000.00	2.42E+02	2.37E+03	3.52E+03	4.90E+03	7.10E+03	1.07E+04	1.56E+04	2.01E+04	2.27E+04	2.29E+04	2.39E+04	2.88E+04
15	A	1	$10,000.00	5.38E-01	1.94E+00	2.41E+00	2.81E+00	3.73E+00	3.89E+00	4.86E+00	6.26E+00	6.17E+00	6.65E+00	6.81E+00	8.10E+00
16	B	2	$100,000.00	1.08E+00	4.68E+00	7.80E+00	1.17E+01	1.96E+01	2.66E+01	4.14E+01	5.31E+01	6.48E+01	8.36E+01	9.39E+01	1.26E+02
17	C	4	$10,000,000.00	2.69E+01	2.60E+02	4.26E+02	5.86E+02	8.40E+02	1.24E+03	1.95E+03	2.52E+03	2.78E+03	3.27E+03	3.38E+03	4.65E+03
18	B	2	$100,000.00	9.50E+00	3.67E+01	5.32E+01	6.86E+01	1.10E+02	1.26E+02	1.70E+02	2.48E+02	2.76E+02	2.84E+02	3.27E+02	3.62E+02
19	C	4	$10,000,000.00	2.37E+02	2.04E+03	2.90E+03	3.43E+03	4.71E+03	5.87E+03	8.01E+03	1.17E+04	1.18E+04	1.11E+04	1.18E+04	1.34E+04

End-State	Class	Severity	Dollar value	Prior Risk	Posterior Risk										
				0	1	2	3	4	5	6	7	8	9	10	11
20	A	1	$10,000.00	2.07E-02	4.48E-02	3.81E-02	4.36E-02	5.30E-02	5.60E-02	6.37E-02	7.86E-02	7.87E-02	7.38E-02	7.58E-02	8.34E-02
21	A	1	$10,000.00	3.17E-03	1.21E-02	1.37E-02	1.61E-02	2.16E-02	2.35E-02	2.84E-02	3.82E-02	3.84E-02	3.55E-02	3.75E-02	4.06E-02
22	B	2	$100,000.00	6.35E-03	2.92E-02	4.42E-02	6.70E-02	1.13E-01	1.60E-01	2.42E-01	3.24E-01	4.03E-01	4.46E-01	5.17E-01	6.30E-01
23	C	4	$10,000,000.00	1.59E-01	1.62E+00	2.41E+00	3.35E+00	4.85E+00	7.47E+00	1.14E+01	1.53E+01	1.73E+01	1.75E+01	1.86E+01	2.33E+01
24	A	1	$10,000.00	3.53E-04	1.33E-03	1.65E-03	1.92E-03	2.55E-03	2.72E-03	3.55E-03	4.77E-03	4.70E-03	5.06E-03	5.31E-03	6.57E-03
25	B	2	$100,000.00	7.05E-04	3.21E-03	5.34E-03	8.01E-03	1.34E-02	1.85E-02	3.02E-02	4.05E-02	4.94E-02	6.37E-02	7.32E-02	1.02E-01
26	C	4	$10,000,000.00	1.76E-02	1.78E-01	2.91E-01	4.01E-01	5.74E-01	8.65E-01	1.42E+00	1.92E+00	2.12E+00	2.49E+00	2.63E+00	3.77E+00
27	B	2	$100,000.00	6.22E-03	2.51E-02	3.64E-02	4.70E-02	7.52E-02	8.78E-02	1.24E-01	1.89E-01	2.10E-01	2.16E-01	2.55E-01	2.93E-01
28	C	4	$10,000,000.00	1.56E-01	1.40E+00	1.99E+00	2.35E+00	3.22E+00	4.10E+00	5.85E+00	8.95E+00	9.01E+00	8.46E+00	9.17E+00	1.09E+01
29	A	1	$10,000.00	4.17E-04	1.10E-03	9.37E-04	1.07E-03	1.30E-03	1.50E-03	1.84E-03	2.45E-03	2.45E-03	2.30E-03	2.35E-03	2.96E-03
30	A	1	$10,000.00	6.38E-05	2.97E-04	3.36E-04	3.95E-04	5.30E-04	6.29E-04	8.23E-04	1.19E-03	1.19E-03	1.10E-03	1.17E-03	1.44E-03
31	B	2	$100,000.00	1.28E-04	7.17E-04	1.09E-03	1.65E-03	2.78E-03	4.29E-03	7.00E-03	1.01E-02	1.25E-02	1.39E-02	1.61E-02	2.23E-02
32	C	4	$10,000,000.00	3.19E-03	3.98E-02	5.92E-02	8.23E-02	1.19E-01	2.00E-01	3.29E-01	4.77E-01	5.38E-01	5.43E-01	5.78E-01	8.28E-01
33	A	1	$10,000.00	7.09E-06	3.27E-05	4.06E-05	4.72E-05	6.27E-05	7.29E-05	1.03E-04	1.49E-04	1.46E-04	1.58E-04	1.65E-04	2.33E-04
34	B	2	$100,000.00	1.42E-05	7.88E-05	1.31E-04	1.97E-04	3.29E-04	4.97E-04	8.75E-04	1.26E-03	1.54E-03	1.98E-03	2.27E-03	3.61E-03
35	C	4	$10,000,000.00	3.54E-04	4.38E-03	7.16E-03	9.84E-03	1.41E-02	2.32E-02	4.12E-02	5.97E-02	6.58E-02	7.76E-02	8.18E-02	1.34E-01
36	B	2	$100,000.00	1.25E-04	6.17E-04	8.95E-04	1.15E-03	1.85E-03	2.35E-03	3.60E-03	5.88E-03	6.54E-03	6.72E-03	7.91E-03	1.04E-02
37	C	4	$10,000,000.00	3.13E-03	3.43E-02	4.88E-02	5.77E-02	7.92E-02	1.10E-01	1.70E-01	2.79E-01	2.80E-01	2.63E-01	2.85E-01	3.86E-01
38	C	4	$10,000,000.00	7.78E-03	2.49E-02	2.47E-02	2.96E-02	3.92E-02	4.90E-02	6.72E-02	9.63E-02	1.03E-01	1.02E-01	1.10E-01	1.48E-01
39	B	2	$100,000.00	1.27E-06	3.59E-06	3.59E-06	4.43E-06	6.17E-06	7.50E-06	1.03E-05	1.60E-05	1.76E-05	1.80E-05	1.99E-05	2.86E-05
40	C	4	$10,000,000.00	3.18E-05	1.99E-04	1.96E-04	2.21E-04	2.64E-04	3.50E-04	4.83E-04	7.58E-04	7.54E-04	7.03E-04	7.16E-04	1.06E-03
41	A	1	$10,000.00	7.50E+01	8.03E+01	7.96E+01	7.94E+01	8.58E+01	9.56E+01	1.02E+02	1.07E+02	1.14E+02	1.24E+02	1.35E+02	1.50E+02
42	A	1	$10,000.00	9.79E-01	9.83E-01	1.11E+00	1.06E+00	1.05E+00	1.08E+00	1.11E+00	1.10E+00	1.18E+00	1.39E+00	1.52E+00	1.69E+00
43	A	1	$10,000.00	1.50E-01	2.66E-01	3.99E-01	3.91E-01	4.28E-01	4.53E-01	4.97E-01	5.36E-01	5.75E-01	6.67E-01	7.55E-01	8.24E-01
44	B	2	$100,000.00	3.00E-01	6.41E-01	1.29E+00	1.63E+00	2.25E+00	3.09E+00	4.23E+00	4.54E+00	6.04E+00	8.39E+00	1.04E+01	1.28E+01
45	C	4	$10,000,000.00	7.49E+00	3.56E+01	7.04E+01	8.15E+01	9.63E+01	1.44E+02	1.99E+02	2.15E+02	2.59E+02	3.28E+02	3.75E+02	4.73E+02
46	A	1	$10,000.00	1.66E-02	2.92E-02	4.82E-02	4.68E-02	5.06E-02	5.25E-02	6.22E-02	6.69E-02	7.04E-02	9.53E-02	1.07E-01	1.33E-01

End-State	Class	Severity	Dollar value	Prior Risk	Posterior Risk										
				0	1	2	3	4	5	6	7	8	9	10	11
47	B	2	$100,000.00	3.33E-02	7.04E-02	1.56E-01	1.95E-01	2.66E-01	3.58E-01	5.28E-01	5.68E-01	7.40E-01	1.20E+00	1.47E+00	2.07E+00
48	C	4	$10,000,000.00	8.32E-01	3.91E+00	8.51E+00	9.75E+00	1.14E+01	1.67E+01	2.49E+01	2.69E+01	3.17E+01	4.69E+01	5.30E+01	7.65E+01
49	B	2	$100,000.00	2.94E-01	5.52E-01	1.06E+00	1.14E+00	1.49E+00	1.69E+00	2.18E+00	2.65E+00	3.15E+00	4.07E+00	5.13E+00	5.95E+00
50	C	4	$10,000,000.00	7.34E+00	3.06E+01	5.81E+01	5.71E+01	6.40E+01	7.91E+01	1.02E+02	1.26E+02	1.35E+02	1.59E+02	1.85E+02	2.21E+02
51	A	1	$10,000.00	2.45E-01	5.46E-01	4.64E-01	5.30E-01	7.00E-01	8.10E-01	9.42E-01	1.19E+00	1.26E+00	1.30E+00	1.43E+00	1.69E+00
52	A	1	$10,000.00	3.74E-02	1.48E-01	1.66E-01	1.96E-01	2.85E-01	3.40E-01	4.20E-01	5.76E-01	6.16E-01	6.25E-01	7.10E-01	8.24E-01
53	B	2	$100,000.00	7.49E-02	3.56E-01	5.37E-01	8.15E-01	1.50E+00	2.32E+00	3.57E+00	4.89E+00	6.47E+00	7.86E+00	9.79E+00	1.28E+01
54	C	4	$10,000,000.00	1.87E+00	1.98E+01	2.93E+01	4.07E+01	6.42E+01	1.08E+02	1.68E+02	2.32E+02	2.77E+02	3.08E+02	3.52E+02	4.73E+02
55	A	1	$10,000.00	4.16E-03	1.62E-02	2.01E-02	2.34E-02	3.37E-02	3.93E-02	5.26E-02	7.20E-02	7.54E-02	8.93E-02	1.00E-01	1.33E-01
56	B	2	$100,000.00	8.32E-03	3.91E-02	6.50E-02	9.74E-02	1.77E-01	2.68E-01	4.47E-01	6.11E-01	7.92E-01	1.12E+00	1.38E+00	2.06E+00
57	C	4	$10,000,000.00	2.08E-01	2.17E+00	3.54E+00	4.87E+00	7.59E+00	1.25E+01	2.10E+01	2.89E+01	3.39E+01	4.40E+01	4.98E+01	7.64E+01
58	B	2	$100,000.00	7.34E-02	3.06E-01	4.43E-01	5.71E-01	9.94E-01	1.27E+00	1.84E+00	2.85E+00	3.37E+00	3.81E+00	4.82E+00	5.95E+00
59	C	4	$10,000,000.00	1.83E+00	1.70E+01	2.42E+01	2.85E+01	4.26E+01	5.93E+01	8.66E+01	1.35E+02	1.45E+02	1.49E+02	1.74E+02	2.20E+02
60	A	1	$10,000.00	1.60E-04	3.74E-04	3.17E-04	3.62E-04	4.79E-04	5.65E-04	6.88E-04	9.05E-04	9.62E-04	9.92E-04	1.12E-03	1.37E-03
61	A	1	$10,000.00	2.45E-05	1.01E-04	1.14E-04	1.34E-04	1.95E-04	2.37E-04	3.07E-04	4.39E-04	4.69E-04	4.76E-04	5.53E-04	6.68E-04
62	B	2	$100,000.00	4.91E-05	2.44E-04	3.68E-04	5.57E-04	1.02E-03	1.62E-03	2.61E-03	3.73E-03	4.93E-03	5.99E-03	7.63E-03	1.04E-02
63	C	4	$10,000,000.00	1.23E-03	1.35E-02	2.01E-02	2.79E-02	4.39E-02	7.55E-02	1.23E-01	1.77E-01	2.11E-01	2.34E-01	2.75E-01	3.84E-01
64	A	1	$10,000.00	2.73E-06	1.11E-05	1.37E-05	1.60E-05	2.31E-05	2.75E-05	3.84E-05	5.49E-05	5.75E-05	6.81E-05	7.83E-05	1.08E-04
65	B	2	$100,000.00	5.45E-06	2.68E-05	4.45E-05	6.67E-05	1.21E-04	1.87E-04	3.26E-04	4.66E-04	6.03E-04	8.56E-04	1.08E-03	1.67E-03
66	C	4	$10,000,000.00	1.36E-04	1.49E-03	2.43E-03	3.33E-03	5.19E-03	8.74E-03	1.54E-02	2.21E-02	2.59E-02	3.35E-02	3.88E-02	6.20E-02
67	B	2	$100,000.00	4.81E-05	2.10E-04	3.03E-04	3.91E-04	6.80E-04	8.87E-04	1.34E-03	2.17E-03	2.57E-03	2.90E-03	3.76E-03	4.82E-03
68	C	4	$10,000,000.00	1.20E-03	1.16E-02	1.66E-02	1.95E-02	2.91E-02	4.14E-02	6.32E-02	1.03E-01	1.10E-01	1.14E-01	1.35E-01	1.79E-01
69	A	1	$10,000.00	3.22E-06	9.18E-06	7.80E-06	8.90E-06	1.18E-05	1.52E-05	1.99E-05	2.82E-05	2.99E-05	3.09E-05	3.47E-05	4.86E-05
70	A	1	$10,000.00	4.93E-07	2.48E-06	2.79E-06	3.29E-06	4.79E-06	6.36E-06	8.89E-06	1.37E-05	1.46E-05	1.48E-05	1.72E-05	2.37E-05
71	B	2	$100,000.00	9.86E-07	5.98E-06	9.04E-06	1.37E-05	2.51E-05	4.34E-05	7.56E-05	1.16E-04	1.53E-04	1.86E-04	2.37E-04	3.67E-04
72	C	4	$10,000,000.00	2.47E-05	3.32E-04	4.93E-04	6.85E-04	1.08E-03	2.02E-03	3.56E-03	5.49E-03	6.57E-03	7.30E-03	8.53E-03	1.36E-02
73	A	1	$10,000.00	5.48E-08	2.73E-07	3.38E-07	3.93E-07	5.66E-07	7.36E-07	1.11E-06	1.71E-06	1.79E-06	2.12E-06	2.43E-06	3.83E-06

End-State	Class	Severity	Dollar value	Prior Risk	Posterior Risk										
				0	1	2	3	4	5	6	7	8	9	10	11
74	B	2	$100,000.00	1.10E-07	6.57E-07	1.09E-06	1.64E-06	2.97E-06	5.02E-06	9.45E-06	1.45E-05	1.88E-05	2.66E-05	3.35E-05	5.94E-05
75	C	4	$10,000,000.00	2.74E-06	3.65E-05	5.96E-05	8.19E-05	1.27E-04	2.34E-04	4.45E-04	6.87E-04	8.05E-04	1.04E-03	1.21E-03	2.20E-03
76	B	2	$100,000.00	9.67E-07	5.15E-06	7.45E-06	9.60E-06	1.67E-05	2.38E-05	3.89E-05	6.77E-05	8.00E-05	9.04E-05	1.17E-04	1.71E-04
77	C	4	$10,000,000.00	2.42E-05	2.86E-04	4.07E-04	4.80E-04	7.16E-04	1.11E-03	1.83E-03	3.20E-03	3.43E-03	3.54E-03	4.20E-03	6.34E-03
78	C	4	$10,000,000.00	6.01E-05	2.08E-04	2.06E-04	2.46E-04	3.55E-04	4.95E-04	7.26E-04	1.11E-03	1.25E-03	1.37E-03	1.63E-03	2.43E-03
79	B	2	$100,000.00	9.82E-09	2.99E-08	2.99E-08	3.68E-08	5.57E-08	7.57E-08	1.11E-07	1.84E-07	2.15E-07	2.41E-07	2.93E-07	4.71E-07
80	C	4	$10,000,000.00	2.45E-07	1.66E-06	1.63E-06	1.84E-06	2.39E-06	3.53E-06	5.21E-06	8.72E-06	9.21E-06	9.44E-06	1.06E-05	1.74E-05
81	A	1	$10,000.00	8.33E+00	9.81E+00	9.73E+00	9.70E+00	1.04E+01	1.16E+01	1.21E+01	1.27E+01	1.33E+01	1.44E+01	1.69E+01	2.34E+01
82	A	1	$10,000.00	1.09E-01	1.20E-01	1.36E-01	1.30E-01	1.27E-01	1.31E-01	1.33E-01	1.30E-01	1.38E-01	1.61E-01	1.91E-01	2.64E-01
83	A	1	$10,000.00	1.66E-02	3.25E-02	4.88E-02	4.78E-02	5.17E-02	5.48E-02	5.95E-02	6.33E-02	6.73E-02	7.73E-02	9.44E-02	1.29E-01
84	B	2	$100,000.00	3.33E-02	7.83E-02	1.58E-01	1.99E-01	2.72E-01	3.74E-01	5.05E-01	5.37E-01	7.07E-01	9.72E-01	1.30E+00	2.00E+00
85	C	4	$10,000,000.00	8.32E-01	4.35E+00	8.60E+00	9.96E+00	1.16E+01	1.74E+01	2.38E+01	2.55E+01	3.03E+01	3.80E+01	4.69E+01	7.40E+01
86	A	1	$10,000.00	1.85E-03	3.57E-03	5.89E-03	5.72E-03	6.12E-03	6.35E-03	7.43E-03	7.92E-03	8.24E-03	1.10E-02	1.33E-02	2.08E-02
87	B	2	$100,000.00	3.70E-03	8.61E-03	1.91E-02	2.38E-02	3.21E-02	4.33E-02	6.32E-02	6.72E-02	8.66E-02	1.39E-01	1.84E-01	3.23E-01
88	C	4	$10,000,000.00	9.25E-02	4.78E-01	1.04E+00	1.19E+00	1.38E+00	2.02E+00	2.97E+00	3.18E+00	3.71E+00	5.43E+00	6.63E+00	1.20E+01
89	B	2	$100,000.00	3.26E-02	6.74E-02	1.30E-01	1.40E-01	1.80E-01	2.05E-01	2.60E-01	3.14E-01	3.69E-01	4.71E-01	6.41E-01	9.30E-01
90	C	4	$10,000,000.00	8.16E-01	3.75E+00	7.10E+00	6.98E+00	7.73E+00	9.56E+00	1.22E+01	1.49E+01	1.58E+01	1.84E+01	2.31E+01	3.45E+01
91	A	1	$10,000.00	2.72E-02	6.67E-02	5.67E-02	6.47E-02	8.46E-02	9.79E-02	1.13E-01	1.40E-01	1.48E-01	1.51E-01	1.79E-01	2.64E-01
92	A	1	$10,000.00	4.16E-03	1.80E-02	2.03E-02	2.39E-02	3.45E-02	4.11E-02	5.03E-02	6.82E-02	7.21E-02	7.24E-02	8.88E-02	1.29E-01
93	B	2	$100,000.00	8.32E-03	4.35E-02	6.57E-02	9.96E-02	1.81E-01	2.80E-01	4.27E-01	5.78E-01	7.57E-01	9.10E-01	1.22E+00	2.00E+00
94	C	4	$10,000,000.00	2.08E-01	2.42E+00	3.58E+00	4.98E+00	7.76E+00	1.31E+01	2.01E+01	2.74E+01	3.24E+01	3.56E+01	4.41E+01	7.39E+01
95	A	1	$10,000.00	4.62E-04	1.98E-03	2.45E-03	2.86E-03	4.08E-03	4.76E-03	6.28E-03	8.52E-03	8.83E-03	1.03E-02	1.26E-02	2.08E-02
96	B	2	$100,000.00	9.24E-04	4.78E-03	7.94E-03	1.19E-02	2.14E-02	3.24E-02	5.34E-02	7.23E-02	9.27E-02	1.30E-01	1.73E-01	3.22E-01
97	C	4	$10,000,000.00	2.31E-02	2.65E-01	4.33E-01	5.95E-01	9.17E-01	1.51E+00	2.51E+00	3.42E+00	3.97E+00	5.09E+00	6.23E+00	1.19E+01
98	B	2	$100,000.00	8.15E-03	3.74E-02	5.42E-02	6.98E-02	1.20E-01	1.53E-01	2.20E-01	3.37E-01	3.95E-01	4.41E-01	6.02E-01	9.30E-01
99	C	4	$10,000,000.00	2.04E-01	2.08E+00	2.96E+00	3.49E+00	5.15E+00	7.16E+00	1.04E+01	1.60E+01	1.69E+01	1.73E+01	2.17E+01	3.44E+01
100	A	1	$10,000.00	1.78E-05	4.57E-05	3.88E-05	4.43E-05	5.79E-05	6.83E-05	8.23E-05	1.07E-04	1.13E-04	1.15E-04	1.40E-04	2.14E-04

End-State	Class	Severity	Dollar value	Prior Risk	Posterior Risk										
				0	1	2	3	4	5	6	7	8	9	10	11
101	A	1	$10,000.00	2.73E-06	1.23E-05	1.39E-05	1.64E-05	2.36E-05	2.87E-05	3.67E-05	5.20E-05	5.49E-05	5.52E-05	6.92E-05	1.04E-04
102	B	2	$100,000.00	5.45E-06	2.98E-05	4.50E-05	6.81E-05	1.24E-04	1.96E-04	3.12E-04	4.41E-04	5.77E-04	6.94E-04	9.54E-04	1.62E-03
103	C	4	$10,000,000.00	1.36E-04	1.65E-03	2.45E-03	3.41E-03	5.30E-03	9.13E-03	1.47E-02	2.09E-02	2.47E-02	2.71E-02	3.43E-02	5.99E-02
104	A	1	$10,000.00	3.03E-07	1.36E-06	1.68E-06	1.96E-06	2.79E-06	3.32E-06	4.59E-06	6.50E-06	6.73E-06	7.88E-06	9.78E-06	1.69E-05
105	B	2	$100,000.00	6.06E-07	3.27E-06	5.44E-06	8.15E-06	1.46E-05	2.26E-05	3.90E-05	5.51E-05	7.06E-05	9.91E-05	1.35E-04	2.61E-04
106	C	4	$10,000,000.00	1.51E-05	1.82E-04	2.96E-04	4.07E-04	6.27E-04	1.06E-03	1.84E-03	2.61E-03	3.03E-03	3.88E-03	4.86E-03	9.68E-03
107	B	2	$100,000.00	5.34E-06	2.56E-05	3.71E-05	4.77E-05	8.22E-05	1.07E-04	1.61E-04	2.57E-04	3.01E-04	3.36E-04	4.70E-04	7.54E-04
108	C	4	$10,000,000.00	1.34E-04	1.42E-03	2.02E-03	2.39E-03	3.52E-03	5.00E-03	7.56E-03	1.22E-02	1.29E-02	1.32E-02	1.69E-02	2.79E-02
109	A	1	$10,000.00	3.58E-07	1.12E-06	9.53E-07	1.09E-06	1.42E-06	1.83E-06	2.38E-06	3.33E-06	3.50E-06	3.57E-06	4.34E-06	7.60E-06
110	A	1	$10,000.00	5.48E-08	3.03E-07	3.41E-07	4.02E-07	5.79E-07	7.69E-07	1.06E-06	1.62E-06	1.71E-06	1.72E-06	2.15E-06	3.70E-06
111	B	2	$100,000.00	1.10E-07	7.31E-07	1.10E-06	1.67E-06	3.04E-06	5.24E-06	9.04E-06	1.37E-05	1.79E-05	2.16E-05	2.96E-05	5.74E-05
112	C	4	$10,000,000.00	2.74E-06	4.06E-05	6.02E-05	8.37E-05	1.30E-04	2.45E-04	4.25E-04	6.50E-04	7.69E-04	8.45E-04	1.07E-03	2.13E-03
113	A	1	$10,000.00	6.09E-09	3.33E-08	4.13E-08	4.80E-08	6.85E-08	8.90E-08	1.33E-07	2.02E-07	2.09E-07	2.45E-07	3.04E-07	5.98E-07
114	B	2	$100,000.00	1.22E-08	8.03E-08	1.34E-07	2.00E-07	3.59E-07	6.07E-07	1.13E-06	1.71E-06	2.20E-06	3.08E-06	4.19E-06	9.28E-06
115	C	4	$10,000,000.00	3.04E-07	4.46E-06	7.28E-06	1.00E-05	1.54E-05	2.83E-05	5.32E-05	8.12E-05	9.42E-05	1.21E-04	1.51E-04	3.44E-04
116	B	2	$100,000.00	1.07E-07	6.29E-07	9.11E-07	1.17E-06	2.02E-06	2.87E-06	4.65E-06	8.00E-06	9.36E-06	1.05E-05	1.46E-05	2.67E-05
117	C	4	$10,000,000.00	2.69E-06	3.50E-05	4.97E-05	5.86E-05	8.65E-05	1.34E-04	2.19E-04	3.79E-04	4.01E-04	4.09E-04	5.25E-04	9.90E-04
118	C	4	$10,000,000.00	6.68E-06	2.54E-05	2.51E-05	3.01E-05	4.29E-05	5.98E-05	8.68E-05	1.31E-04	1.47E-04	1.59E-04	2.04E-04	3.80E-04
119	B	2	$100,000.00	1.09E-09	3.66E-09	3.65E-09	4.50E-09	6.74E-09	9.16E-09	1.32E-08	2.18E-08	2.52E-08	2.79E-08	3.67E-08	7.36E-08
120	C	4	$10,000,000.00	2.73E-08	2.03E-07	1.99E-07	2.25E-07	2.89E-07	4.27E-07	6.23E-07	1.03E-06	1.08E-06	1.09E-06	1.32E-06	2.72E-06
121	A	1	$10,000.00	1.25E+01	1.33E+01	1.31E+01	1.31E+01	1.39E+01	1.86E+01	1.94E+01	2.01E+01	2.09E+01	2.45E+01	2.61E+01	2.82E+01
122	A	1	$10,000.00	1.63E-01	1.62E-01	1.84E-01	1.75E-01	1.70E-01	2.11E-01	2.13E-01	2.07E-01	2.17E-01	2.75E-01	2.93E-01	3.19E-01
123	A	1	$10,000.00	2.50E-02	4.39E-02	6.59E-02	6.46E-02	6.92E-02	8.85E-02	9.51E-02	1.00E-01	1.06E-01	1.32E-01	1.45E-01	1.55E-01
124	B	2	$100,000.00	4.99E-02	1.06E-01	2.13E-01	2.69E-01	3.64E-01	6.03E-01	8.08E-01	8.52E-01	1.11E+00	1.66E+00	2.00E+00	2.41E+00
125	C	4	$10,000,000.00	1.25E+00	5.88E+00	1.16E+01	1.35E+01	1.56E+01	2.81E+01	3.80E+01	4.04E+01	4.76E+01	6.49E+01	7.22E+01	8.91E+01
126	A	1	$10,000.00	2.77E-03	4.82E-03	7.96E-03	7.72E-03	8.19E-03	1.02E-02	1.19E-02	1.26E-02	1.30E-02	1.88E-02	2.06E-02	2.51E-02
127	B	2	$100,000.00	5.55E-03	1.16E-02	2.58E-02	3.22E-02	4.30E-02	6.98E-02	1.01E-01	1.07E-01	1.36E-01	2.37E-01	2.83E-01	3.89E-01

End-State	Class	Severity	Dollar value	Prior Risk	Posterior Risk										
				0	1	2	3	4	5	6	7	8	9	10	11
128	C	4	$10,000,000.00	1.39E-01	6.46E-01	1.40E+00	1.61E+00	1.84E+00	3.26E+00	4.76E+00	5.05E+00	5.83E+00	9.27E+00	1.02E+01	1.44E+01
129	B	2	$100,000.00	4.90E-02	9.11E-02	1.76E-01	1.89E-01	2.41E-01	3.31E-01	4.16E-01	4.97E-01	5.80E-01	8.04E-01	9.87E-01	1.12E+00
130	C	4	$10,000,000.00	1.22E+00	5.06E+00	9.59E+00	9.43E+00	1.03E+01	1.54E+01	1.96E+01	2.36E+01	2.48E+01	3.15E+01	3.55E+01	4.15E+01
131	A	1	$10,000.00	4.08E-02	9.01E-02	7.66E-02	8.74E-02	1.13E-01	1.58E-01	1.80E-01	2.23E-01	2.32E-01	2.57E-01	2.76E-01	3.18E-01
132	A	1	$10,000.00	6.24E-03	2.44E-02	2.74E-02	3.23E-02	4.61E-02	6.63E-02	8.04E-02	1.08E-01	1.13E-01	1.24E-01	1.37E-01	1.55E-01
133	B	2	$100,000.00	1.25E-02	5.87E-02	8.87E-02	1.35E-01	2.42E-01	4.52E-01	6.84E-01	9.17E-01	1.19E+00	1.55E+00	1.88E+00	2.40E+00
134	C	4	$10,000,000.00	3.12E-01	3.26E+00	4.84E+00	6.73E+00	1.04E+01	2.11E+01	3.22E+01	4.34E+01	5.10E+01	6.08E+01	6.79E+01	8.90E+01
135	A	1	$10,000.00	6.93E-04	2.68E-03	3.31E-03	3.86E-03	5.46E-03	7.68E-03	1.01E-02	1.35E-02	1.39E-02	1.76E-02	1.93E-02	2.51E-02
136	B	2	$100,000.00	1.39E-03	6.45E-03	1.07E-02	1.61E-02	2.86E-02	5.23E-02	8.54E-02	1.15E-01	1.46E-01	2.22E-01	2.67E-01	3.89E-01
137	C	4	$10,000,000.00	3.47E-02	3.59E-01	5.85E-01	8.04E-01	1.23E+00	2.44E+00	4.02E+00	5.43E+00	6.25E+00	8.69E+00	9.60E+00	1.44E+01
138	B	2	$100,000.00	1.22E-02	5.06E-02	7.32E-02	9.43E-02	1.61E-01	2.48E-01	3.52E-01	5.35E-01	6.20E-01	7.53E-01	9.28E-01	1.12E+00
139	C	4	$10,000,000.00	3.06E-01	2.81E+00	3.99E+00	4.71E+00	6.89E+00	1.16E+01	1.66E+01	2.53E+01	2.66E+01	2.95E+01	3.34E+01	4.15E+01
140	A	1	$10,000.00	2.67E-05	6.17E-05	5.24E-05	5.98E-05	7.74E-05	1.10E-04	1.32E-04	1.70E-04	1.77E-04	1.96E-04	2.15E-04	2.58E-04
141	A	1	$10,000.00	4.09E-06	1.67E-05	1.88E-05	2.21E-05	3.15E-05	4.63E-05	5.87E-05	8.24E-05	8.64E-05	9.41E-05	1.07E-04	1.26E-04
142	B	2	$100,000.00	8.18E-06	4.02E-05	6.07E-05	9.20E-05	1.66E-04	3.16E-04	4.99E-04	6.99E-04	9.07E-04	1.18E-03	1.47E-03	1.95E-03
143	C	4	$10,000,000.00	2.04E-04	2.23E-03	3.31E-03	4.60E-03	7.10E-03	1.47E-02	2.35E-02	3.31E-02	3.89E-02	4.63E-02	5.29E-02	7.22E-02
144	A	1	$10,000.00	4.54E-07	1.83E-06	2.27E-06	2.64E-06	3.73E-06	5.36E-06	7.34E-06	1.03E-05	1.06E-05	1.34E-05	1.51E-05	2.03E-05
145	B	2	$100,000.00	9.08E-07	4.42E-06	7.34E-06	1.10E-05	1.96E-05	3.66E-05	6.24E-05	8.74E-05	1.11E-04	1.69E-04	2.08E-04	3.15E-04
146	C	4	$10,000,000.00	2.27E-05	2.45E-04	4.00E-04	5.50E-04	8.39E-04	1.71E-03	2.94E-03	4.14E-03	4.76E-03	6.62E-03	7.48E-03	1.17E-02
147	B	2	$100,000.00	8.02E-06	3.46E-05	5.01E-05	6.45E-05	1.10E-04	1.73E-04	2.57E-04	4.08E-04	4.73E-04	5.74E-04	7.23E-04	9.08E-04
148	C	4	$10,000,000.00	2.00E-04	1.92E-03	2.73E-03	3.22E-03	4.71E-03	8.07E-03	1.21E-02	1.93E-02	2.03E-02	2.25E-02	2.60E-02	3.36E-02
149	A	1	$10,000.00	5.37E-07	1.51E-06	1.29E-06	1.47E-06	1.90E-06	2.96E-06	3.81E-06	5.28E-06	5.51E-06	6.10E-06	6.68E-06	9.16E-06
150	A	1	$10,000.00	8.22E-08	4.10E-07	4.61E-07	5.43E-07	7.75E-07	1.24E-06	1.70E-06	2.56E-06	2.69E-06	2.93E-06	3.31E-06	4.46E-06
151	B	2	$100,000.00	1.64E-07	9.88E-07	1.49E-06	2.26E-06	4.07E-06	8.46E-06	1.45E-05	2.18E-05	2.82E-05	3.68E-05	4.56E-05	6.92E-05
152	C	4	$10,000,000.00	4.11E-06	5.49E-05	8.14E-05	1.13E-04	1.74E-04	3.95E-04	6.80E-04	1.03E-03	1.21E-03	1.44E-03	1.64E-03	2.56E-03
153	A	1	$10,000.00	9.13E-09	4.50E-08	5.57E-08	6.49E-08	9.16E-08	1.44E-07	2.13E-07	3.21E-07	3.29E-07	4.18E-07	4.68E-07	7.21E-07
154	B	2	$100,000.00	1.83E-08	1.09E-07	1.80E-07	2.70E-07	4.81E-07	9.80E-07	1.81E-06	2.72E-06	3.46E-06	5.26E-06	6.45E-06	1.12E-05

End-State	Class	Severity	Dollar value	Prior Risk	Posterior Risk										
				0	1	2	3	4	5	6	7	8	9	10	11
155	C	4	$10,000,000.00	4.57E-07	6.03E-06	9.84E-06	1.35E-05	2.06E-05	4.57E-05	8.50E-05	1.29E-04	1.48E-04	2.06E-04	2.32E-04	4.14E-04
156	B	2	$100,000.00	1.61E-07	8.50E-07	1.23E-06	1.58E-06	2.70E-06	4.64E-06	7.44E-06	1.27E-05	1.47E-05	1.79E-05	2.24E-05	3.22E-05
157	C	4	$10,000,000.00	4.03E-06	4.72E-05	6.71E-05	7.92E-05	1.16E-04	2.16E-04	3.50E-04	6.01E-04	6.31E-04	6.99E-04	8.08E-04	1.19E-03
158	C	4	$10,000,000.00	1.00E-05	3.43E-05	3.40E-05	4.06E-05	5.74E-05	9.66E-05	1.39E-04	2.08E-04	2.31E-04	2.71E-04	3.13E-04	4.58E-04
159	B	2	$100,000.00	1.64E-09	4.94E-09	4.93E-09	6.08E-09	9.01E-09	1.48E-08	2.12E-08	3.45E-08	3.96E-08	4.77E-08	5.64E-08	8.86E-08
160	C	4	$10,000,000.00	4.09E-08	2.75E-07	2.69E-07	3.04E-07	3.86E-07	6.90E-07	9.97E-07	1.64E-06	1.70E-06	1.87E-06	2.03E-06	3.28E-06
161	A	1	$10,000.00	1.80E+00	1.60E+00	1.37E+00	1.31E+00	1.27E+00	1.72E+00	1.62E+00	1.58E+00	1.55E+00	1.69E+00	1.70E+00	1.76E+00
162	A	1	$10,000.00	2.75E-01	4.33E-01	4.91E-01	4.82E-01	5.19E-01	7.24E-01	7.23E-01	7.68E-01	7.54E-01	8.10E-01	8.43E-01	8.55E-01
163	B	2	$100,000.00	5.50E-01	1.04E+00	1.59E+00	2.01E+00	2.72E+00	4.94E+00	6.14E+00	6.51E+00	7.92E+00	1.02E+01	1.16E+01	1.33E+01
164	C	4	$10,000,000.00	1.38E+01	5.80E+01	8.66E+01	1.00E+02	1.17E+02	2.30E+02	2.89E+02	3.08E+02	3.39E+02	3.98E+02	4.18E+02	4.91E+02
165	A	1	$10,000.00	3.06E-02	4.76E-02	5.93E-02	5.77E-02	6.14E-02	8.38E-02	9.03E-02	9.60E-02	9.23E-02	1.16E-01	1.19E-01	1.38E-01
166	B	2	$100,000.00	6.12E-02	1.15E-01	1.92E-01	2.40E-01	3.22E-01	5.71E-01	7.68E-01	8.14E-01	9.70E-01	1.45E+00	1.64E+00	2.14E+00
167	C	4	$10,000,000.00	1.53E+00	6.38E+00	1.05E+01	1.20E+01	1.38E+01	2.67E+01	3.61E+01	3.86E+01	4.16E+01	5.69E+01	5.92E+01	7.94E+01
168	B	2	$100,000.00	5.40E-01	8.99E-01	1.31E+00	1.41E+00	1.81E+00	2.71E+00	3.16E+00	3.80E+00	4.13E+00	4.93E+00	5.72E+00	6.18E+00
169	C	4	$10,000,000.00	1.35E+01	5.00E+01	7.14E+01	7.04E+01	7.76E+01	1.26E+02	1.49E+02	1.80E+02	1.77E+02	1.93E+02	2.06E+02	2.29E+02
170	A	1	$10,000.00	1.18E-03	1.10E-03	9.38E-04	8.94E-04	8.71E-04	1.20E-03	1.18E-03	1.21E-03	1.18E-03	1.28E-03	1.33E-03	1.42E-03
171	A	1	$10,000.00	1.80E-04	2.97E-04	3.36E-04	3.30E-04	3.55E-04	5.06E-04	5.28E-04	5.85E-04	5.75E-04	6.17E-04	6.57E-04	6.93E-04
172	B	2	$100,000.00	3.61E-04	7.15E-04	1.09E-03	1.38E-03	1.86E-03	3.45E-03	4.49E-03	4.96E-03	6.03E-03	7.76E-03	9.06E-03	1.07E-02
173	C	4	$10,000,000.00	9.02E-03	3.97E-02	5.93E-02	6.88E-02	7.98E-02	1.61E-01	2.11E-01	2.35E-01	2.59E-01	3.04E-01	3.26E-01	3.98E-01
174	A	1	$10,000.00	2.00E-05	3.26E-05	4.06E-05	3.95E-05	4.20E-05	5.85E-05	6.60E-05	7.32E-05	7.04E-05	8.81E-05	9.29E-05	1.12E-04
175	B	2	$100,000.00	4.01E-05	7.86E-05	1.31E-04	1.64E-04	2.20E-04	3.99E-04	5.61E-04	6.21E-04	7.39E-04	1.11E-03	1.28E-03	1.74E-03
176	C	4	$10,000,000.00	1.00E-03	4.37E-03	7.17E-03	8.22E-03	9.44E-03	1.86E-02	2.64E-02	2.94E-02	3.17E-02	4.34E-02	4.61E-02	6.43E-02
177	B	2	$100,000.00	3.54E-04	6.16E-04	8.96E-04	9.64E-04	1.24E-03	1.89E-03	2.31E-03	2.90E-03	3.15E-03	3.76E-03	4.46E-03	5.01E-03
178	C	4	$10,000,000.00	8.84E-03	3.42E-02	4.89E-02	4.82E-02	5.30E-02	8.82E-02	1.09E-01	1.37E-01	1.35E-01	1.47E-01	1.61E-01	1.85E-01
179	A	1	$10,000.00	2.37E-05	2.69E-05	2.30E-05	2.20E-05	2.14E-05	3.23E-05	3.43E-05	3.75E-05	3.67E-05	4.00E-05	4.12E-05	5.05E-05
180	A	1	$10,000.00	3.63E-06	7.29E-06	8.25E-06	8.11E-06	8.72E-06	1.35E-05	1.53E-05	1.82E-05	1.79E-05	1.92E-05	2.04E-05	2.46E-05
181	B	2	$100,000.00	7.25E-06	1.76E-05	2.67E-05	3.38E-05	4.58E-05	9.24E-05	1.30E-04	1.54E-04	1.88E-04	2.41E-04	2.81E-04	3.81E-04

End-State	Class	Severity	Dollar value	Prior Risk	Posterior Risk										
				0	1	2	3	4	5	6	7	8	9	10	11
182	C	4	$10,000,000.00	1.81E-04	9.76E-04	1.46E-03	1.69E-03	1.96E-03	4.31E-03	6.11E-03	7.32E-03	8.05E-03	9.45E-03	1.01E-02	1.41E-02
183	A	1	$10,000.00	4.03E-07	8.01E-07	9.97E-07	9.69E-07	1.03E-06	1.57E-06	1.91E-06	2.28E-06	2.19E-06	2.74E-06	2.89E-06	3.97E-06
184	B	2	$100,000.00	8.06E-07	1.93E-06	3.23E-06	4.04E-06	5.41E-06	1.07E-05	1.62E-05	1.93E-05	2.30E-05	3.45E-05	3.98E-05	6.16E-05
185	C	4	$10,000,000.00	2.01E-05	1.07E-04	1.76E-04	2.02E-04	2.32E-04	4.99E-04	7.64E-04	9.15E-04	9.85E-04	1.35E-03	1.43E-03	2.28E-03
186	B	2	$100,000.00	7.11E-06	1.51E-05	2.20E-05	2.37E-05	3.04E-05	5.06E-05	6.69E-05	9.01E-05	9.79E-05	1.17E-04	1.38E-04	1.78E-04
187	C	4	$10,000,000.00	1.78E-04	8.40E-04	1.20E-03	1.18E-03	1.30E-03	2.36E-03	3.15E-03	4.27E-03	4.20E-03	4.58E-03	4.98E-03	6.58E-03
188	C	4	$10,000,000.00	4.42E-04	6.09E-04	6.08E-04	6.07E-04	6.45E-04	1.05E-03	1.25E-03	1.48E-03	1.54E-03	1.78E-03	1.93E-03	2.52E-03
189	B	2	$100,000.00	7.22E-08	8.80E-08	8.83E-08	9.08E-08	1.01E-07	1.61E-07	1.90E-07	2.45E-07	2.63E-07	3.13E-07	3.48E-07	4.89E-07
190	C	4	$10,000,000.00	1.80E-06	4.89E-06	4.82E-06	4.54E-06	4.35E-06	7.53E-06	8.96E-06	1.16E-05	1.13E-05	1.22E-05	1.25E-05	1.81E-05

Table C-3. Risk values for the ISOM unit over the 11 year period

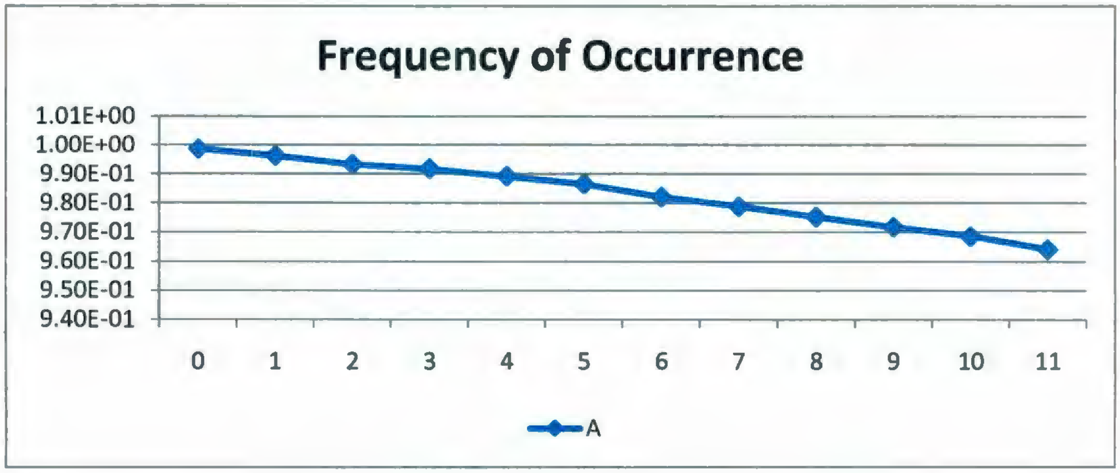

Figure C-2. Frequency of occurrence of process upsets in the ISOM unit

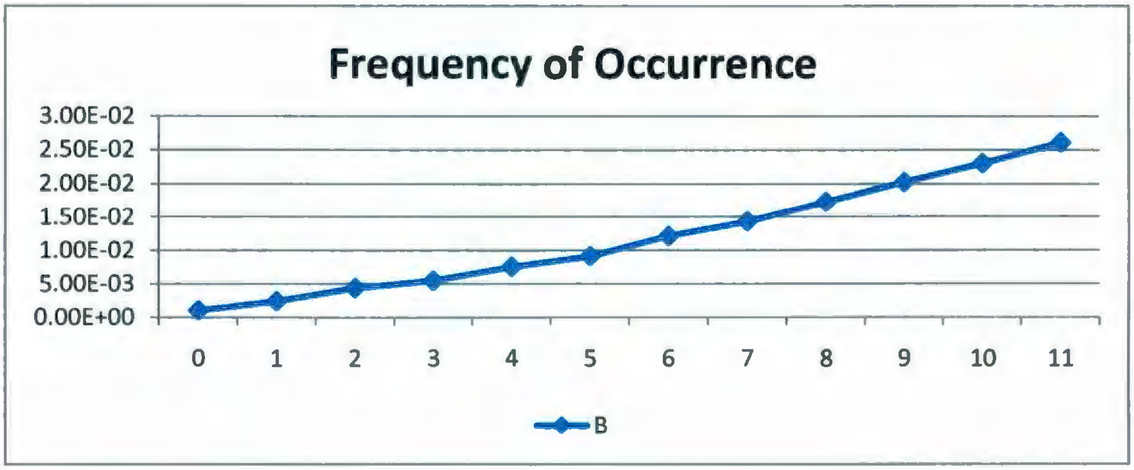

Figure C-3. Frequency of occurrence of process shutdown in the ISOM unit

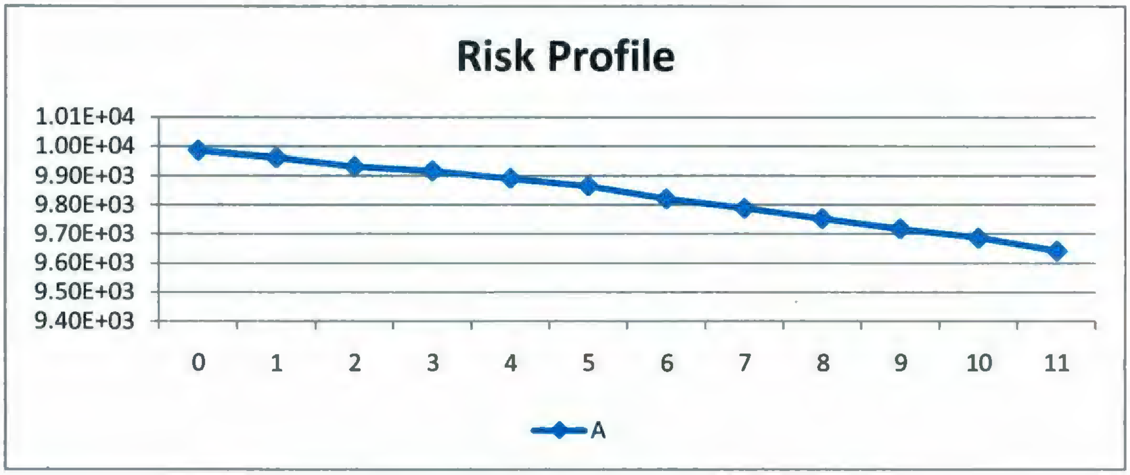

Figure C-4. Risk profile of process upsets in the ISOM unit

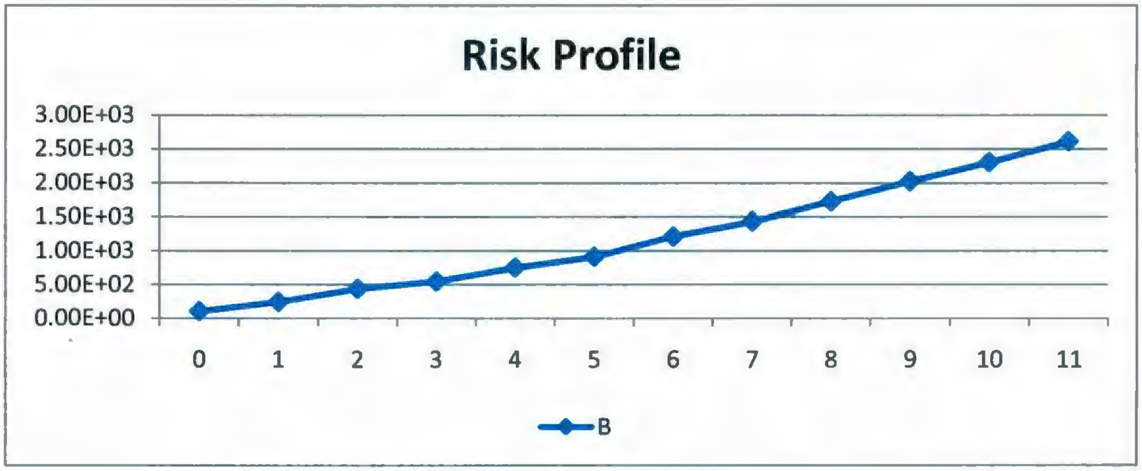

Figure C-5. Risk profile of process shutdown in the ISOM unit