RISK ASSESSMENT BY FAULT TREE ANALYSIS OF METHANE EXPLOSIONS IN TURKISH HARD COAL ENTERPRISES UNDERGROUND MINES

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ABSTRACT

RISK ASSESSMENT BY FAULT TREE ANALYSIS OF METHANE EXPLOSIONS IN TURKISH HARD COAL ENTERPRISES UNDERGROUND MINES

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Mining is one of the most hazardous industries in the world. Among all mining professions, underground coal mining has the highest occupational accident and disease rates. Methane explosion appears as the major accident type which results in severe loss of life and property in underground coal mining. Including underground coal mines, preparing a practicable risk assessment is the primary step to sustain a safe workplace environment. The main objective of this study is to specify the root causes of methane explosions in underground hard coal mines by performing quantitative risk assessment. Total of 67 methane explosions resulted in 815 fatalities between the years 1875 and 2014 within Turkish Hard Coal Enterprises (TTK), which is the major hard coal producer in Turkey, are evaluated in order to achieve the goal. A deductive risk analysis technique, fault tree analysis (FTA), was implemented in order to specify the root causes of methane explosions.

The methodology starts with examining the occupational accident statistics gathered from TTK. Using the data, events and gates of the fault tree were constructed by a step-wise approach. Major and minor causes of methane explosions were identified by utilising ReliaSoft BlockSim-7 software.

Research findings revealed that mechanical ignitions are the most significant failure event for a possible methane explosion. It is followed by deficient ventilation practice, methane outburst, blasting, and electrical ignition, respectively. The time period in which a methane explosion has a 100% probability to occur was found as 108 months. Excluding the most significant failure event mechanical ignitions from the fault tree, the period increases to 255 months. Besides the quantitative FTA, also qualitative FTA was conducted. Qualitative fault tree has 27 intermediate events and 65 basic events (root causes) which make it a comprehensive fault tree of methane explosions among other studies in the field. This study, as being the first implementation of FTA for methane explosions in Turkish underground coal mines, is expected to contribute to mining industry and current literature in various ways. Research area could be extended in the future studies from TTK to Turkish coal mining industry, including also the private sector companies. The monotype 5 x 5 matrix risk analysis practice in the country could be improved by raising the awareness of coal industry to the comprehensive nature of FTA approach and performing FTA at mining companies. A general guide to prevent methane explosions could be prepared by considering the root causes on the fault tree and it could also contribute to the provisions of national occupational safety and health legislation. The ultimate goal is to prevent possible accidents caused by methane explosions.

Keywords: Fault tree analysis (FTA), methane explosions, occupational safety and health (OSH), risk assessment, underground coal mining.

ÖZ

TÜRKİYE TAŞKÖMÜRÜ KURUMU YERALTI MADENLERİNDE METAN PATLAMALARININ HATA AĞACI ANALİZİ YÖNTEMİYLE RİSK DEĞERLENDİRMESİ

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Madencilik dünyanın en tehlikeli sektörlerinin başında gelir. Tüm madencilik işkolları arasında yeraltı kömür madenciliği her zaman en yüksek iş kazası ve meslek hastalığı oranlarına sahip olmuştur. Ciddi can ve mal kaybı ile sonuçlanan birincil kaza tipi grizu patlamasıdır. Yeraltı kömür madenciliği dâhil tüm sektörlerde uygulanabilir bir risk değerlendirmesi, güvenli bir işyeri ortamı sağlayabilmenin birincil şartıdır. Bu çalışmanın amacı kantitatif bir risk değerlendirmesi ile yeraltı taşkömürü madenlerindeki grizu patlamalarının kök nedenlerini belirlemektir. Amaç doğrultusunda, ülkenin birincil taşkömürü üreticisi konumundaki Türkiye Taşkömürü Kurumunda (TTK) 1875-2014 yılları arasında meydana gelen ve toplamda 815 can kaybı ile sonuçlanan 67 grizu patlaması incelenmiştir. Patlamaların kök nedenlerini belirlerken bir tümdengelim risk analizi tekniği olan hata ağacı analizinden (HAA) faydalanılmıştır.

Çalışmaya TTK iş kazası verilerinin incelenmesi ile başlanmıştır. Bu veriler kullanılarak hata ağacının olayları ve kapıları aşamalı bir yaklaşım ile oluşturulmuştur. Grizu patlamalarının ana sebepleri ve yan sebepleri, ReliaSoft BlockSim-7 yazılımı kullanılarak belirlenmiştir.

Araştırma bulgularına göre olası bir grizu patlamasında mekanik tutuşma kaynakları en büyük etkiye sahiptir. Onu sırasıyla hatalı havalandırma, metan degajı, patlatma ve elektrik tutuşma kaynakları izlemektedir. Bir grizu patlaması gerçekleşmesinin %100 olasılık ile beklendiği zaman aralığı 108 ay olarak bulunmuştur. En kritik hata olayı olan mekanik tutuşma kaynağının sistemden çıkarılması ile bu zaman aralığı 255 aya yükselmiştir. Araştırmada kantitatif analizin yanında kalitatif HAA de yürütülmüştür. Kalitatif ağaçta 27 orta dereceli ve 65 basit olay (kök neden) tespit edilmiştir ve diğer grizu patlamaları çalışmaları ile karşılaştırıldığında kapsamlı bir HAA sunulmaktadır. Grizu patlamalarının hata ağacı yöntemiyle Türkiye'de ilk defa sunulduğu bu çalışmanın madencilik sektörü ve literatüre çeşitli yönlerden katkı sağlaması beklenmektedir. Gelecekte çalışmanın kapsamı TTK'dan daha geniş tutulabilir ve özel sektör işyerleri de dâhil Türkiye kömür madenciliğinde çeşitli diğer maden kazaları incelenebilir. Ülkede uygulanmakta olan tek tip risk analizi yöntemi (5 x 5 matrix metodu) sürekli gelişmekte olan iş sağlığı ve güvenliği göz önünde bulundurularak daha üst seviyeye çıkarılabilir ve HAA'nın tümdengelim yaklaşımı ile kapsamlı yapısı sektörün dikkatini çekebilir. Kök nedenler göz önüne alınarak grizu patlamalarına karşı genel bir önleme stratejisi geliştirilip uygulamaya alınarak madenlerde iş sağlığı ve güvenliği yasal mevzuatına da katkı sağlanabilir. Çalışmanın nihai amacı, grizu patlamalarından kaynaklı ölüm ve yaralanmaların önlenmesine bir şekilde katkı sağlayabilmektir.

Anahtar Kelimeler: Hata ağacı analizi (HAA), grizu patlamaları, iş sağlığı ve güvenliği (İSG), risk değerlendirmesi, yeraltı kömür madenciliği.

To my parents

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CHAPTER 1

INTRODUCTION

1.1 Background Information

International Labor Organization (ILO) indicated that occupational accidents and work-related diseases caused over 2.3 million fatalities in 2014. In addition to this, it was estimated that there were over 313 million non-fatal occupational accidents requiring at least four days of absence from work (ILO, 2014). The cost of these occupational accidents could be substantial. It was estimated that occupational safety and health (OSH) practices cover 4% of global Gross Domestic Product (GDP) each year (ILO, 2014).

Mining industry due to its inherent nature of the bussiness, has the highest accident frequency rates when compared to other industries especially in developing countries. Although developed countries has reached a certain level at reducing the number of accidents and occupational diseases in mining, there are still many nations, such as Turkey, who suffer from humanitarian, financial, and legal consequences of health and safety deficiencies. Besides its environmental hazards such as land disturbance, water pollution and air emission rates; coal mining, specifically, has the highest occupational accidents and fatalities in the industry. According to the report of Turkish Statistical Institute (TUIK, 2014), in 2013, 2.3% of the employees in Turkey had an occupational accident and 2.1% of them had an occupational disease. Among those, mining and quarrying takes the first place as the class of occupation with its 10.4% employee share in the sector. Moreover, 5.5% of mining and quarrying employees had different types of occupational diseases and it is the highest share among all other classes (TUIK, 2014).

Between 1900 and 2008, 11,615 underground coal mine workers died in 514 United States of America (U. S. A.) underground coal mining disasters (Kowalski-Trakofler and Brnich, 2010). Considering both accident and fatality numbers, methane explosion takes the first place by 81.7% and 89.5%, respectively (Table 1.1). According to Mine Safety and Health Administration (MSHA, 2015), there have been a total of 65 fatalities and 18 injuries in the U.S.A. underground coal mines due to explosions over the past decade. In other countries, such as China, Russia, Turkey, and Ukraine, the explosion statistics are even worse. Between 1875-2014, 67 methane explosions have resulted in 815 fatalities in Zonguldak coal basin (TTK, 2015).

Table 1.1 Number of underground coal mine accidents and fatalities by type of the disaster from 1900 to 2008 (Kowalski-Trakofler, 2010)

Accident Type	**Number of Accidents**	**Number of Fatalities**
Explosion	420	10,390
Fire	35	727
Haulage	21	145
Roof and Rib Fall	14	92
Inundation	7	62
Miscellaneous	17	199
TOTAL	**514**	**11,615**

1.2 Problem Statement

From the beginning of its history, underground coal mining is one of the most dangerous occupations in the world. Although there is a noticeable effort to decrease the number of occupational accidents and diseases in recent years, the statistics are still unsatisfactory. Among all accident types in mining, methane explosion appears as the most catastrophic one. The primary step to prevent methane explosions is identifying the hazards and risks specific to each mine and generating an effective risk assessment to evaluate them. Despite its essentiality, number and extent of quantitative risk assessment studies dealing with methane explosions are limited. Also, existing FTA studies in the world generally have a basic approach and do not specify the root causes of explosions in detail.

Besides, the monotype risk assessment by 5 x 5 risk matrix practice used in Turkey should be taken to a more advanced level, considering the ongoing OSH progress in the world. Mine explosions, generally occuring in a similar manner, are inexcusable in the 21st century and should be settled by the actions of all stakeholders in the industry. It is a multi-leveled problem which has to be dealt with a step-wise prevention strategy for both individuals and public administrations.

1.3 Objectives and Scope of the Study

The primary objective of this research study is to perform fault tree analysis (FTA) in order to specify and evaluate root causes of methane explosions in underground coal mines. The scope of this research study includes accidents occured in the five enterprises within Turkish Hard Coal Enterprises (TTK) between 1875 and 2014. The components of this main objective are:

1. Obtaining statistical data of occupational accidents occured in TTK between 1875-2014,
2. Generating a databese related to methane explosions occured in TTK,
3. Conducting an FTA for methane explosions for TTK in order to specify the root causes and preventive measures of explosions, and
4. Developing a methane explosion prevention strategy based on the obtained research results.

1.4 Research Methodology

The research methodology essentially entails five main stages. These stages are listed as:

i. Pre-processing the data considering methane explosions and other occupational accidents that may trigger a methane explosion,
ii. Determination of main causes and prevention measures of methane explosions,
iii. Generation and analyses of FTA for methane explosion using BlockSim© 7 (2011) software developed by ReliaSoft Corporation,
iv. Determination of the probability distributions of basic events using Weibull++ 7 (2011) software developed by ReliaSoft Corporation, and
v. Specifying the primary causes of methane explosions, according to probability of occurences.

1.5 Expected Scientific and Industrial Contributions

The study suggests a quantitative risk analysis of methane explosions in underground coal mines using FTA technique. The primary contribution of the study is that it is the first application of a comprehensive quantitative risk analysis method for methane explosions in underground coal mines. The current literature lacks information related to analyzing the root causes of explosions in detail via a fault tree. This study comprises a first example within this framework.

The current risk analysis examples in the country are monotype and has to be improved by considering recent OSH progress in the world. The primary expected industrial contribution of this study is that it brings a new proposal and approach to risk analysis practices. Further applications of the risk analysis could decrease the risk of methane explosions and also accidents caused by explosions.

1.6 Structure of the Thesis

This thesis is composed of five chapters. Following the introductory chapter, Chapter 2 presents a comprehensive literature survey. Literature survey includes information related to OSH in the world and also in Turkey, using representative occupational accident and disease statistics, especially focusing on underground coal mining. Then, the nature of methane explosions with their causes and prevention measures are described. Towards the end of this chapter, risk assessment methods are briefly described and finally, detailed information about FTA and some applications of FTA in engineering are described.

The third chapter presents information about the study area and the data. Then, in Chapter 4, both qualitative and quantitative FTA's are conducted. Qualitative FTA consists of brief explanations of all intermediate and basic events, while quantitative FTA is about probability distributions and statistical inferences. Finally, Chapter 5 presents the results of FTA, discussions and main conclusions drawn from the study, and recommendations for future studies.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

There is a noticeable effort to decrease occupational accidents and diseases in underground coal mining especially considering the last decades. For instance, Poplin *et al.* (2008) indicated that from 1996 to 2003, lost-time injuries per 100,000 miners declined 20% in the U.S.A., 78% in Queensland, and 52% in New South Wales. Also incident rate ratios for each region decreased by 11%, 72%, and 44%, respectively. It is considered that the differential decline in ratios among Australian states comparing to the U.S.A. depends on the application of risk-based health and safety regulations in Australia consisting mainly three steps: risk identification, qualitative or quantitative risk analysis, and reviewing of the recommended corrective actions (Poplin *et al.*, 2008). Despite these efforts, mining still remains one of the most dangerous occupations.

Countries such as Australia, Canada and the United Kingdom are referred as the most successful world leaders in OSH practices in general (Bahn, 2013). Proactive management of risks have an important contribution in this success. Australia is also one of the biggest coal producer countries in the world, along with China, the U. S. A., and India (Arslanhan and Cünedioğlu, 2010). Turkey has 0.2% of the world's coal reserve and placed at the 4th rank among 35 countries considering lignite production. On the other hand, Turkey is placed at the 44th rank among 50 countries considering hard coal production. Turkey's total coal production's 3% comes from hard coal and 97% comes from lignite mining (Arslanhan and Cünedioğlu, 2010).

However, in terms of fatalities per million ton of coal produced is 30 times higher for hard coal mining than lignite mining in 2007.

The comparison of Turkish OSH statistics with other countries is significant: Over 200 people a year lose their lives at work in Britain. Besides, around 150,000 nonfatal injuries are reported each year, and an estimated 2 million suffer from work-related illness (Chen and Zorigt, 2013). In Turkey, from 1991 to 2008, 2,554 miners had lost their life and 13,087 workers had become permanently disabled to work in coal mining industry (Arslanhan and Cünedioğlu, 2010). In terms of annual fatality rates, only Turkish mining industry suffers from nearly the same fatality rate of England's whole work life in recent years. For example in 2012, a total of 74,871 occupational accidents resulted in 744 fatalities and 2,209 permanent disabilities in Turkey. Another important coal producer in the world is China. Chinese coal mines are notoriously dangerous with official Chinese statistics showing the fatality rates in coal mines between 4,746 and 6,995 fatalities per year (Saleh and Cummings, 2011). Number of fatalities seems extremely high. However, according to Arslanhan and Cünedioğlu (2010), the number of fatalities per 1 million tons of coal mined in Turkey in 2008 was 7.22, five times the figure for China (1.27) and 361 times the figure for the U.S.A. (0.02) in the same year.

According to MSHA (2015), totally 623 documented mine disasters with five or more fatalities took place in the United States since 1860's in which 13,883 fatalities occured. Most of those accidents were methane and/or coal dust explosions (494 accidents, referring 79% of overall) and 11 of them were caused by asyphxiation (2%). Therefore, briefly speaking, deficiencies in mine ventilation practices were the cause of 81% of all coal mining disasters recorded in the United States. Besides, according to Chen and Zorigt (2013), gas-related accidents caused 43% of all fatalities in coal mines during 2001 and proceed likewise in recent years in China. Similarly, in Turkey, methane and/or coal dust explosions appear as the main reason of the largest coal mining disasters: 1992 Kozlu (263 fatalities), 1983 Armutçuk (103 fatalities), 1990 Amasya (68 fatalities), 1995 Yozgat (37 fatalities), and 2010

Karadon (30 fatalities) are some of the biggest disasters in Turkish mining industry. Until 2014 Soma mine disaster which resulted in 301 fatalities, TTK Kozlu methane explosion was the biggest mining accident and also occupational accident in general in Turkey. Mining accidents and diseases has dramatic humanitarian, financial, and legal consequences, they create huge public concern as well. Any theoretical or practical studies aiming to optimize the prevention strategies are critically important. Jiang *et al*. (2012) emphasized that while roof and rib fall accidents have the highest frequency, methane explosions result in the highest number of fatalities in coal mines.

Hazard identification is the primary step of any OSH study. Risk assessment process also begins with the determination of hazards in workplaces. Underground coal mining hazards are variable in severity from field to field but according to Donoghue (2004), commonly seen ones to be considered during risk assessment studies can be listed as:

- Physical hazards: including noise, heat and humidity, vibration, ambient lighting,
- Chemical hazards: including harmful gases, coal dust and methane explosions, fire, spontaneous combustion, diesel particulate exposures, in some cases cyanide, arsenic, and mercury exposures,
- Biological hazards: malaria, dengue fever, leptospirosis, and ancylostomiasis,
- Ergonomic hazards: fatigue, manual handling, musculoskeletal disorders, remote control of mobile equipment, and
- Psychosocial hazards: post-traumatic stress disorders, drug and alcohol abuse, expatriate placements.

In addition to these hazards, Badri *et al*. (2013) suggested also electrical (direct or alternating current and static electricity), mechanical (vehicles, equipment, moving elements, and transportation), and mine structure (roof and rib fall and subsidence) hazards with human factor (human error, competence, interference, and harassment).

Among all the abovementioned hazards, the most catastrophic one is the methane explosion.

Literature survey was carried out mainly to determine the prevention strategies against methane explosions and examine the previous studies consisting risk assessment of methane explosions. This chapter consists of five sections. General concept of OSH and a brief information about occupational accident causation theories in mining accidents are presented at the beginning. Occupational accident statistics in Turkish mining industry are also given in this Section 2.2. Methane explosions, including their mechanism and prevention strategies, are presented in the following section. Mine ventilation practices and potential ignition sources in underground coal mining are also examined. In this manner, the components of the fault tree presented in Chapter 4 began to be designated. Besides the technical point of view, the role of human error in explosions is discussed. Later on, risk analysis and risk assessment methods in Turkish mining industry and in the world mining are investigated. In the last section, the risk analysis method used in this study, FTA technique, and some applications of FTA considering their gaps or similarities comparing to this study are discussed.

2.2 Occupational Safety and Health Concepts and Practices in Turkey

There are some different definitions of accident in OSH literature. The U. S. Department of Energy (2010) defined accident as an:

> "*unwanted transfer (or release) of energy that, due to the absence or failure of barriers and controls, produces injury to persons, damage to property or reduction in process output*." (Saleh and Cummings, 2011).

McElroy (1981) prefered a simpler point of view and defined accidents as:

> "*unplanned events that interrupt the completion of an activity with or without injury or damage*".

Similarly, injury concept can be defined in several forms. According to Hillson and Murray-Webster (2004), injury is defined as wound or trauma; harm or hurt; or damage inflicted on the body of the injured by an external force. Injury is a bodily lesion resulting from acute overexposure to energy interacting with the body in amounts or rates that exceed the threshold of physiological tolerance. Occupational injuries are caused by two types of energy exposures as acute and chronic (Khanzode *et al.*, 2012).

Besides accident and injury, the main components of OSH are hazard and risk. Hazard is defined as a thing that has potential to cause harm or as a source of danger (Hillson and Murray-Webster, 2004). Identification of hazards is the first step in assessing risk of injury. Besides, according to Khanzode *et al*. (2012), accident literature is divided into five categories as: (i) hazard identification methods, (ii) injury risk assessment methods, (iii) accident and injury causation theories, (iv) injury mechanism models, and (v) accident and injury intervention methods. In this study, first three categories are implemented to methane explosions in underground coal mines by identifying the related hazards, conducting a risk analysis, and investigating accident and injury causation theories briefly.

The other main component of OSH, risk, is defined as the chance of loss, the degree of probability of loss, a situation involving exposure to danger or possibility that something unpleasant will happen (Hillson and Murray-Webster, 2004). Risk can also be defined as the considered expected loss or damage associated with the occurence of a possible undesired event (Kushnir, 1985). Today, implementation of a satisfactory risk assessment is qualified as the primary requirement of a successful and sustainable OSH policy at workplaces. Risk assessment involves identifying the hazards, estimating their likelihood, and estimating the consequences. The details of risk assessment are given in Section 2.4.

The first generation accident causation theories hold a primitive viewpoint towards accident causation. These theories hold a person’s traits and unsafe behavior as responsible for the accident (Greenwood and Woods, 1919). The second generation theories (domino theories) conceptualize a chain of sequential events leading to an accident and call these events as dominos (Heinrich, 1931). Removal of any one domino from the chain would break the chain of accident events. According to Heinrich (1931), 88% of the occupational accidents are the results of unsafe acts of persons, 10% of them are the results of unsafe mechanical or physical conditions and remaining 2% of them are accepted as unpreventable. Despite the base of the study and the reliability of the percentages have not being certified ever, the proportions suggested by Heinrich are usually accepted and have an important role in OSH literature (Manuele, 2011).

Occupational accident statistics in Turkey is mainly collected and presented by Social Security Institution (SGK). According to SGK (2014), 191,389 occupational accidents have resulted in 1,360 fatalities in 2013. Besides, total of 371 occupational diseases have been detected. Incidence rate of work accidents appear as 5.88 (number of accidents per 1,000,000 working hours) and 1.32 (number of accidents per 100 person). Total days of temporary incapacity as year-end of 2013 was 2,357,505. Weight rate of occupational accidents is 507 days, which indicates the lost days in a year due to accidents for 1,000,000 working hours, and 0.41 hours, which indicates the lost hours for each 100 working hours. The highest number of occupational accident fatalities, 197, was due to struck by object in motion, collision with material. The highest number of occupational accident fatalities, 356, in terms of the general activity of the individual at the time of accident occured in excavation, construction, repair, and demolition workers. In terms of the classification of economic activity, building construction is the activity that the highest number of occupational accident fatalities with 296. In the same frame, coal and lignite extraction has 36 fatalities (SGK, 2014). Occupational accident statistics for all sectors between 2008-2012 in Turkey are given in Table 2.1.

Table 2.1 Occupational accident and disease statistics for all sectors between 2008-2012 in Turkey (SGK, 2014)

Year	Number of Accidents	Fatalities
2008	72,963	866
2009	60,754	1,171
2010	62,903	1,454
2011	69,227	1,710
2012	74,871	745

Considering the last 10-year interval of all sectors in Turkey, mean number of occupational accidents per year is 73,477, mean number of occupational diseases per year is 571, mean number of permanent disabilities per year is 1,924, and mean number of fatalities per year is 986. Table 2.2 contains occupational accident and disease statistics for the mining industry between 2008-2012 in Turkey.

Table 2.2 Number of accidents and fatalities of mining industry in general and coal mining in specific between 2008-2012 in Turkey (SGK, 2014)

Year	Number of Accidents		Fatalities	
	Mining	Coal Mining	Mining	Coal Mining
2008	6,516	5,728	66	30
2009	9,091	8,193	20	3
2010	9,064	8,150	131	92
2011	10,558	9,217	122	58
2012	9,963	8,828	44	20

Expanding Table 2.2 and considering the last 10-year interval of mining industry in Turkey, mean number of occupational accidents per year is 7,979, mean number of occupational diseases per year is 351, mean number of permanent disabilities per year is 261, and mean number of fatalities per year is 81.

Considering the 10-year interval of coal and lignite mining in Turkey, mean number of occupational accidents per year is 6,462, mean number of occupational diseases per year is 292, mean number of permanent disabilities per year is 203, and mean number of fatalities per year is 41. The mean number of fatalities for all sectors is 986, for mining industry 81, and for coal and lignite mining 41, according to SGK. In the following section, the most catastrophic risk in underground coal mining, methane explosion is investigated.

2.3 Methane Explosions in Underground Coal Mines

Methane (CH_4) is a colorless, odorless, flammable gas. It has a specific gravity of 0.554 which makes it lighter than air so it is often found near the mine roof. It is just slightly soluble in water. It burns readily in air, forming carbon dioxide (CO_2) and water vapour; the flame is pale, slightly luminous, and very hot. The boiling point of methane is -161.5 °C and the melting point is -182 °C. Mixtures of methane and air are explosive, while methane itself is very stable in general. The amount of methane liberated by the coal depends on the geologic age and type of coal and the depth of the coal deposit (Kurnia and Mujumdar, 2012). Ignition temperature of methane is between 650-750 °C. It does not ignited instantly but after some contact with a heat source. There is a relation between the source's degree of temperature and the contact time. For instance, it is ignited by a 10-second contact to 650 °C, while it is ignited by a 1-second contact to 1,000 °C. Chemical reaction of methane explosion is given in Equation 1.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{(Eq. 1)}$$

McPherson (2015) specified methane explosions:

> "*like airplane crashes, do not occur often but, when they do, have the potential of causing disastrous loss of life and property as well as a temporary or permanent sterilization of mineral reserves*".

Due to its catastrophic results, methane explosion has a distinctive status among other types of mining accidents. A single explosion can enhance the fatality rate in hundreds, especially if they followed by coal dust explosions. Accidents produced by explosions arise from blast effects, burning and, primarily, from the carbon monoxide (CO) content of afterdamp – the mixture of gases produced by the explosion. Although incidences of hydrogen explosions at battery charging stations and ignitions of oil vapours from machines have been also reported the vast majority of gas explosions in mines involve methane (McPherson, 2015).

Methane entering a mine, for example from a crack, progressively mixes with the ventilating air and is diluted. It enters the mine from the coal seam or surroundings 1.6 times faster than the air (Skochinsky and Komarov, 1969). In the event that this progressive dilution reduces the concentration from 100% to 1%, the concentration range of 5% to 15% is known as the explosive range. In this range, the mixture may be ignited. Above 15%, called the upper explosive limit (UEL), methane air mixtures are not explosive, but will become explosive when mixed with more air. Below 5%, called the lower explosive limit (LEL), methane-air mixtures cannot ignite (Kissell, 2006). The strongest explosion takes place with the methane concentration of 9.5%, due to the complete combustion. It means all methane is burnt using all oxygen available, so no methane and no oxygen remain in the mine air after the explosion. Methane always passes through an explosive range during dilution and an effective mine ventilation system will ensure that this passage through the explosive range is as rapid as possible and that the volume of gas mixture in or above the explosive range is minimized.

As Coward explosive triangle in Figure 2.1 indicates, besides methane amount between the explosive range, explosion needs oxygen (higher than 12% by volume) in order to occur. Removing any component of the triangle, the explosion will be extinguished (McPherson, 2015). Ignition of methane is a very dangerous occurence itself. However, it becomes much worse when the shock wave raises combustible dust into air such that it can be ignited by the flame of the burning methane.

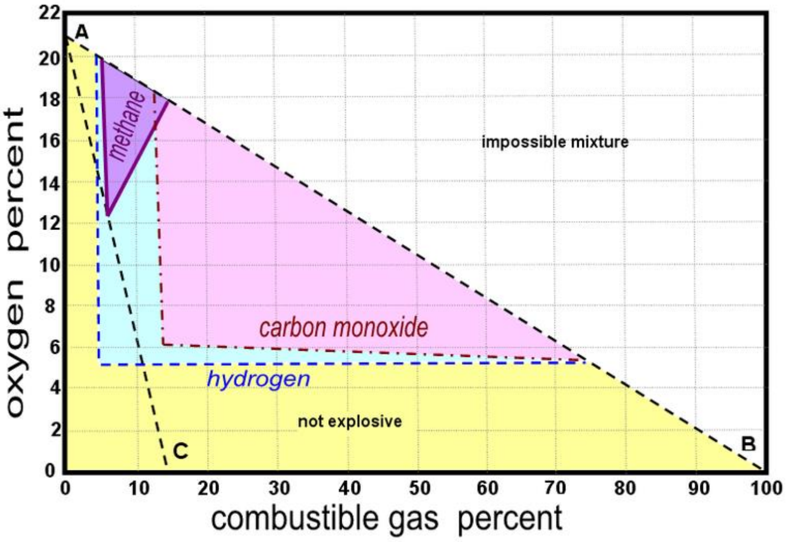


Figure 2.1 Coward explosive triangles (McPherson, 2015)

2.3.1 Control Strategies against Methane Explosions

Examining the explosion mechanism, it can be said that prevention strategies against methane explosions can be summarized under two topics as prevention of explosive atmosphere generation and preventing the ignition of generated explosive atmosphere. Kurnia and Mujumdar (2012) classified methane control strategies into three:

- Before excavation (pre-mining drainage),
- During excavation (fresh air ventilation, water spray, inert ventilation, scrubber ventilation), and
- After excavation (inertisation, post-mining drainage).

Drainage is a pre-mining measure for removing methane. Methane is consistently found in underground coal reserves. The deeper the coal, the higher the pressure and the greater amounts of methane. Distracting methane by drainage will directly reduce the methane emission into mine and also ease the mine ventilation practice. It has also an economic point of view for utilizing the extracted methane. However, methane drainage is not implemented in Turkey. Yet, despite some trials the reasons are assumed as lack of expertise and technical and/or economical infeasibilities of such projects in specific sites.

Outbursts may also be the reason of explosive methane concentration. Methane and in some deposits carbon dioxide are the predominant gases contained in coal. Gas is released as a result of mining coal and the subsequent pressure release in the surrounding strata. At certain concentrations and volumes, these gases cause major risks of explosions and asyphxiation. Harvey and Singh (1998) suggested two crucial prevention strategy against outbursts; effective uses of methane drainage and the management of the outburst risk. Drainage is utilised as the primary mechanism for taking the energy out of an outburst structure and thereby making it safe to mine. Lama and Bodziony (1996) listed the affecting factors of methane outbursts as gas content, permeability, stresses, coal structure, tectonic faults, and the stratigraphic sequence of coal and rock layers. According to Diaz Aguado and Gonzalez Nicieza (2007), the main prevention measures against outburst are specified as gas dilution by ventilation, drainage boreholes, water infusion, and exploitation of a protective coal seam. If gas emissions can not be controlled by ventilation only, gas drainage is necessary. Within the European Union, coal mines in Germany, the United Kingdom, Romania, Poland, and Czech Republic apply gas drainage (Imgrund and Thomas, 2013). If gas contents can not be reduced in a reasonable way, local measures such as, water injection are applied in China. Aziz *et al.* (2011) indicated that over 730 outbursts have occured in Australian mines since 1895 and reducing the pressure and content of gas within the coal seam through focussed gas drainage has been proven in Australia to be the most effective control to ensure that the decreased risk of an outburst.

Besides engineering point of view, human factor is also an important issue to be considered and evaluated during risk assessment process. Human failures occur in all businesses, but the consequences of these mistakes are far more serious in industries where people's lives are at risk. A study by the U.S. Bureau of Mines found that almost 85% of all accidents can be attributed to at least one human error (Rushworth *et al.,* 1999). According to Williamson and Feyer (1990), in Australia, two out of every three occupational accidents can be attributed to human error. Patterson and Shappell (2008) also indicated that there is an evidence and a body of knowledge on the role of human factors in incidents and accidents in areas of aviation, rail, nuclear power, and other safety critical industries.

The specific types of human error that frequently occur in mining accidents are still unknown. To date, a systematic evaluation of mining incident/accident for human error causal factors has not been done. Nonetheless, it can be estimated that human factor (both error or violation types) mostly partakes in roof and rib fall accidents due to the people-oriented characteristic of support occupation. It can be again estimated that the individual acts of workers do not play a significant role at methane explosion occurence. Explosions are mainly caused by unsafe mine environment, design and management, apart from workers initiative and generally their knowledge. Not using the given handheld gas detectors, bringing open flame sources into mine, smoking in the mine, and turning off auxiliary fans may be some of the direct causes of methane explosions and these failures may be associated with the workers, but they can also be eliminated by proper auditing.

2.3.1.1 Mine Ventilation in Underground Coal Mines

Witrant (2013) classified the control processes for total air conditioning into three:

- Quality control – purifying air and removing contaminants such as, gases and dusts,
- Quantity control – regulating the magnitude and direction of air flow through primary ventilation, auxiliary or face ventilation, and local exhaust, and

- Temperature-humidity control – controlling latent and sensible heat by cooling, heating, humidification, and dehumidification.

If the objective is total air conditioning of the mine, then all three goals must be met, and multiple processes may be applied simultaneously. Several processes can serve more than one function; for example, ventilation, the most common one in mining, performs mainly quantity control but may serve also for quality control and temperature-humidity control. Besides, according to Hartman *et al*. (1997), there are also engineering control, medical control, and legal control principles. Engineering control for mine ventilation consists of prevention or avoidance, removal or elimination, suppression or absorption, containment or isolation, and dilution or reduction (Hartman *et al*., 1997). Medical control principles consist of education, physical examinations, lung X-rays, personal protective devices, prophylaxis, and therapy. Finally, legal control principles consist of statutory and regulatory provisions and workers' compensation laws. All are resources to employ in combating environmental hazards.

Primary ventilation system circulate air from the portal to working sections of the mine and considering coal mines, it always employs the mine entries to move air, at least one entry for intake air and at least one entry for return air. While main ventilation systems use mine entries, auxiliary ventilation systems use ventilation duct or line brattice. An average coal mine generally has at least one preproduction gallery where auxiliary ventilation practice is required. It is also required when an effective primary ventilation practice is not sufficient to supply the whole mine openings' air conditioning.

In appropriate circumstances, methane drainage reduces the amount of gas that enters the mine ventilation system (McPherson, 2015). Drainage operation can be applied by horizontal in-seam, in-mine vertical or inclined (cross-measure) boreholes in the roof and floor, vertical wells that have been hydraulically fractured, and short-radius horizontal boreholes drilled from surface (Kurnia and Mujumdar, 2012). As discussed in Section 2.3.1, methane drainage is a control measure at pre-excavation stage of mining and specified as an important prevention strategy against methane explosions, besides its financial benefit to the company. Drainage also reduces the risk of methane outburst.

Watkinson (2014) suggested three requirements for an early detection of any abnormal condition as (i) having enough monitoring locations, (ii) monitoring essential environmental parameters, and (iii) having suitable and properly maintained equipment. Advancing technology allows developed monitoring practices such as, tube bundle systems (TBS). TBS are useful in providing atmospheric data from sealed areas or bleeder systems where the use of electronic sensors is not feasible. To set an example, all Australian coal mines use comprehensive gas monitoring systems based upon handheld instruments, telemetric systems, machine mounted systems, and tube bundle systems supplemented by gas chromatography. Gas monitoring systems are not a control for the hazard. They are established to ensure that the controls sustained in the mine safety management plans are working and to proactively indicate when the system is moving to an uncontrolled state.

2.3.1.2 Ignition Sources in Underground Coal Mines

The second major component of explosion triangle is ignition source. An ignition source must contain sufficient temperature or energy to ignite methane. Methane can be ignited by a minimum ignition temperature of approximately 540 °C (MSHA, 2011). In underground mining operations, there may be various sparking, overheating or open flame sources which can initiate the explosion. One of the possible sources is mechanized equipment. Daily use of these equipment do not pose a threat of ignition. However, as McPherson (2015) emphasized, misuse, lack of proper maintenance, removal or bypassing of safety features such as, diagnostic devices, environmental monitors or thermal trip switches, and running unattended for long periods of time of these equipments are causes of majority of explosions.

Another ignition source may be electrical apparatus. Electrical gear can give rise to incendiary hazards from sparking and overheating. In order to provide a safe-working electrical installation in an underground mine, using permissible equipments, giving particular care to electrical components and junctions, preventing electrostatical discharge and arranging proper charging stations in the mine are crucial (McPherson, 2015).

The main cause of methane ignitions on the working faces of coal mines appears as frictional sparking at the pick points of coal winning machinery. Statistics showed that about 75% of methane ignitions in underground coal mines were caused by frictional ignitions from mining machines, with an additional 4% were caused by frictional ignitions from roof bolters and roof falls (Kawenski *et al.*, 1979). To set an example, the methane explosion happened in Upper Big Branch (2010), which resulted in 29 fatalities, was one of the biggest mining disasters in the U.S.A. considering recent years (Bluestein and Smith, 2010). According to the report of investigation of MSHA (2011), the investigation committee determined that the explosion was ignited by the friction on longwall shearer, which is part of a longwall mining machine and has large rotating cutting drums equipped with bits that cut coal as it moves on a track across the working face, and it led to a methane explosion, then transitioned into coal dust explosions in sequence. McPherson (2015) suggested the two major approaches to reduce this frictional ignition risk are to ensure that there is sufficient ventilation around the cutting drum to provide rapid dilution of the methane as soon as it is emitted, and to quench the cutter pick with water. It will suppress both dust and methane ignitions.

Conveyors are also one of the most likely equipments to be initiated by friction. If the belt becomes immobilized at any point along its length and the drive rollers continue to turn, then high temperatures will be generated at the drive head. The majority of ignitions causing by conveyors can be prevented using belts that do not propagate fire, arranging temperature monitors or belt tension transducers to isolate electrical power from the conveyor drive when an abnormal condition is detected, and collecting dust or spillage around and especially underneath conveyors. Conveyor entries should be well rock-dusted in coal mines (McPherson, 2015).

A study conducted in France showed that explosives are the primary cause of 40% of the methane explosions (Vuillaume and Bigourd, 1986). As it is explained also in Regulation of Occupational Health and Safety in Mining Workplaces published pursuant to 6331 Occupational Safety and Health Act in 2013, in Turkey it is forbidden to use fuse igniters in underground mines containing flammable gases or dust. Electric detonators are permitted instead. Therefore, violating the provision may be the direct cause of a methane explosion. Apart from this, the relevant national or state legislation should be consulted for the conditions under which explosives may be stored or transported underground. Permissible explosives for underground coal mines result in lower heat degrees during and after the blasting. This is satisfied by Sodium Chloride (NaCl) added into the explosives. Similarly, permissible firing systems are preferred because they do not cause open flame and the materials are not easily flammable. Permissible systems should contain an outer body of high conductivity and low susceptible for additional heat, so Copper 22te m detonator is used in order to satisfy these requirements. The failures related to underground blasting operations can be summarized as disuse of firedamp-safe explosives, using excess amount of explosives, failure of delay detonators, not using firedamp-safe blasters, firing using normal grid voltage, problems at firing and junction wires, use of inappropriate testing instruments, stray flux at blasting operations, connection of different manufacturers’ and different resistanced detonators to each other, lack of electrical detonator controls, short distances between blast holes, lack of measuring and control at blastholes, faulty charging of blastholes and incorrect stemming, misfires, improper underground explosive storages, improper explosive crates for transportation. Some examples of methane explosions caused by blasting operations in Turkey are given in Table 2.3.

Table 2.3 Recent examples of methane explosions triggered by underground blasting operations in Turkey (Torun and Tekin, 2011)

Location	Date	Fatalities
Erzurum-Aşkale	2003	7
Karaman-Ermenek	2003	10
Bursa-Mustafakemalpaşa	2009	19
Zonguldak-Karadon	2010	30

Another special consideration mentioned in legislations is welding operations in underground mines. All welding operations that are permitted underground should be carried out under well-controlled conditions. Where there is any possibility of methane or other flammable gases being present then testing for those gases should be carried out before and, at intervals, during welding operations. Moreover, combustible materials such as, coal, wood, paper, and waste rags should be removed from the vicinity of welding operations, fire extinguishers must be available at the sites of all welding operations, and gas containers employed in oxy-acetylene cutting should be stored and used in a secure upright position (McPherson, 2015).

Smoking materials have been suspected as the cause of some fires and explosions in mines. In those mines that have been classified as gassy, carrying such materials into the subsurface is illegal. Well-chosen examples during training and refresher classes, also regular internal auditing mechanism are required actions in order to avoid this risk. Long time ago, ignitions caused by damaged safety lamps were also a concern, but the lamps fall into disuse on a large scale at the present time. Dubaniewicz (2009) conducted a study considering the U.S.A. underground coal mines and explosions using MSHA database. Ignition sources linked to 160 methane and/or coal dust explosion fatalities in mines from 1976 to 2006 are given in Table 2.4.

Table 2.4 Ignition sources considering 160 methane and/or coal dust explosion fatalities in underground coal mines from 1976 to 2006 (Dubaniewicz, 2009)

Source of Ignition	**Percentage (%)**
Nonpermissible equipment	28
Smoking materials	19
Explosives	13
Faulted permissible equipment	11
Torch or welder	9
Roof fall	9
Lightning	8
Continuous miner bits	1
Blasting cap	1
Messenger wire	1
TOTAL	**100.00**

Deficiencies related to permissible equipments (nonpermissible or faulted permissible equipments) have the share of 28% among ignition sources. Smoking materials also draw the attention for having a share of 19%. Besides the U.S.A. coal mines, Table 2.5 shows the results of a similar study conducted between 1976-2000 in Ukrainian mines. It is seen from the table that electric current ignitions were the biggest cause of explosions in Ukraine, considering the given time interval. It can be assumed that most of the electrical ignitions are again due to the utilization of permissible equipments. They are followed by friction sparks and blasting operations. Both Table 2.4 and Table 2.5 reveal similar results for possible ignition sources of methane explosions.

Table 2.5 Ignition sources of the accidents resulted in injury or death (TTK, 2013)

Source of Ignition	**Number of Accidents**	**Percentage (%)**
Electric current	50	46
Friction sparks	21	20
Blasting operations	18	17
Self-ignition of coal	8	7
Cigarette/Open flame	5	5
Flame cutting etc.	5	5
TOTAL	**107**	**100**

2.3.2 Methane Explosions in the U. S. A.

From the beginning of its underground coal mining history, the U.S.A. have suffered from methane explosions. Table 2.6 indicates some of the methane explosions with their location, date, brief explanations, and results in the U.S.A. throughout the 20th century.

Table 2.6 Some of the methane explosions with their brief explanations and results in U. S. mining industry (MSHA, 2015)

Location and Date of the Explosion	Brief Explanation	Fatalities
Stag Canyon No. 2, 1913	Overcharged shot in a dusty pillar section	263
Castle Gate No. 2, 1924	Attempting to relight the key-locked safety lamp	172
Mather No. 1, 1928	Methane accumulation by an open mandoor	195
Centralia Mine, 1947	Insufficiently charged shot	111
Orient No. 2, 1951	Ignited due to an arc from electrical equipment	119

Besides Table 2.6, examining the methane explosions resulted in fatalities and occured more currently, in last 10 years, and brief deficiencies underlined in the accident reports of MSHA is important (MSHA, 2015). For example, the explosion occured at Darby Mine, Kentucky in 2006 (5 fatalities) was reported as the result of insufficient ventilation, insufficient tests for methane, insufficient bleeder systems and seals, not applying rock dust liberally and not cleaning up loose coal, coal dust or other combustible material around welding operation. According to accident investigation reports of MSHA, failing to comply with approved ventilation and roof control plans and poor blasting practices were the main causes of the methane explosion occured in RandD Coal Mine in 2006 which resulted in one fatality. Deficiencies in blasting practice are summarized as lack of gas monitoring before detonating, not handling and loading of explosives by properly trained persons, and lack of tests conducted using a blasting multimeter, galvanometer or other instrument designed specifically. Considering recent years, the two major attention-grabbing methane explosions in the U.S.A. mining industry were 2006 Sago (12 fatalities) and 2010 Upper Big Branch (29 fatalities). Explosion in Sago was mainly associated with again ineffective bleeder systems and seals, lack of special precautions when mining near or into inaccessible areas, and lack of frequent tests for methane. Upper Big Branch explosion is the worst mining disaster in the U.S.A. mining industry since 1970, in Finley Coal Company where 38 miners were killed. Investigation reports of MSHA (2015) indicated that ineffective ventilation system, inadequate methane and oxygen checks, lack of water sprays and dust collectors, and inadequate maintenance of coal winning machinery were the major causes of the explosion. The JWR No. 5 mine is located in Tuscaloosa County, Alabama. It is one of the deepest coal seams in the United States, and when mined, it liberates high quantities of methane and as a result is considered ‘‘very gassy.’’ A roof fall occurred followed by a methane explosion in 2001, and 55 minutes later another more powerful methane and coal dust explosion occurred claiming the lives of 13 miners (Saleh and Cummings, 2011).

The deficiencies caused the methane explosions are usually similar to each other. The need for a proper ventilation, gas monitoring, dust suppression, and blasting operations draw attention at accident reports. Concordantly, Kissell *et al*. (2007) suggested that the three major precautions against methane explosions are providing adequate ventilation, regular monitoring of gas concentrations, and the elimination of ignition sources. Also, McPherson (2015) emphasized that the primary safegueards against methane explosions are a well-designed and operated ventilation system and planned maintenance of equipment.

Up to this point, formation and scientific causes of methane explosions, prevention strategies, and sample methane explosions from the world mining industry are discussed. In the following section, risk analysis studies are examined, in which the aforementioned risks and their evaluations take place.

2.4 Risk Assessment Methods of Methane Explosions

Brown (1993) qualified risk assessment as a forward-looking approach to identify and control hazards (proactive attitude), as opposed to the traditional safety approach of responding to accidents that have already occured (reactive attitude). This distinction is significant to underground mining, where the variety of geological conditions encountered and excavation methods employed make each project somewhat unique.

Risk assessment consists of basically four steps, namely hazard analysis, consequence analysis, likelihood assessment, and risk estimation (Curcuru *et al.*, 2013). Rasche (2001) suggested that until relevant hazards have been clarified, no specific risk analysis method should be chosen. Risk assessment methodologies are classified as qualitative methods and quantitative methods (Tixier, 2002). Quantitative risk assessment requires the estimation of frequency and consequence severity in quantitative terms. This approach is suitable when the risks are high, costs of detailed analyses are justified, and relevant data is available. Qualitative risk assessment is more suitable when risks are low and small number of categories can cover entire range of consequences and likelihoods.

In order to utilize a quantitative risk analysis, two main types of input data are required: Event frequencies or an equivalent numerical descriptor such as, mean time to failure, probability of failure or failure rate, and consequence estimates that describe credible outcomes linked to the event or failure of the item or the system. Despite its size, the mining industry lacks such data, which in part has limited the application of quantitative risk analysis methods in the industry. Weibull (1951) statistics are generally utilized to analyse time to failure statistics.

In an industry such as, mining, risk assessment studies aiming to manage the risks and lower their effects by proper control measures are crucial. However, risk assessment studies of underground coal mining can be qualified as limited for

Turkish mining industry. Although there is a noticeable effort in recent years considering OSH discipline in general, number of theoretical and practical studies aiming to succeed the adaptation of risk analysis to underground coal mining is still limited comparing to developed countries, especially considering methane explosions.

According to Rasche (2001) catastrophic risks can be assessed using fault tree and event tree methods in estimating the likely range of risks. While HAZOP (Hazard and Operability Studies) and “What if” techniques give outputs of simple lists of individual failures, FTA give numerical estimates of system failure probabilities, ETA (Event Tree Analysis) and PRA (Probabilistic Risk Analysis) give listings of event scenarios and their likelihoods and FORM (First Order Reliability Methods) give numerical system failure probabilities and sensitivities to input variables.

Rasche (2001) classified the system safety characteristics of different risk analysis techniques. According to this classification, “What if”, FMEA (Failure Mode and Effect Analysis), HAZOP, and HEA (Human Error Analysis) have limited system reliabilities. While Reliability Block Diagrams, ETA, and FORM are first stage of reliability, FTA and PRA and PSA (Probabilistic Risk and Safety Assessment) are better, second stage reliabilities. Monte Carlo Methods reliability level depends on the model. FTA was specified as an expensive, time-consuming, but effective technique.

Sarı *et al*. (2004) examined the effects of conventional and mechanized systems separately from the safety aspect and evaluated the relation between them. The study focused on West Lignites Management (Garp Linyitleri İşletmesi, GLİ) Tunçbilek-Ömerler and Aegean Lignites Management (Ege Linyitleri İşletmesi, ELİ) Soma-Eynez underground coal mines. The accidents happened at mines were analyzed by their cause, location, injured part of the body, occupation, and the age of the victims; and came to the conclusion of caved ins, manual handling, and material hitting are the most common types of accidents. The most injured parts of the body are the body itself, hands and feet, and the most risky occupations are pickmans and support workers.

Another study is Düzgün and Einstein’s (2004) risk and decision analysis modelling for underground coal mines focusing on cave ins after examining 12 different mines in the U.S.A. The proposed technique was considered as a powerful one in order to overcome the uncertainties at caved in management. Düzgün (2005) analyzed the caved ins resulted in injury or fatalities which happened in Zonguldak hard coal basin between 1986-2003 and proposed a risk assessment methodology. Önder and Adıgüzel (2009) has studied the accidents resulted in fatalities in TTK Enterprises between 1980-2004 by fit analysis and hierarchical loglinear methods. They concluded as production workers are the most affected ones from the accidents. Besides, caved ins and methane explosions are the major causes of fatalities.

Önder *et al.* (2011) constituted a 5 x 5 matrix (Likelihood x Severity) after examining the accidents happened in GLİ surface and underground coal mines separately between 2005-2009. It was found as fall of materials, caved ins, material hitting, and manual handling are the major causes of underground mine accidents. Fall of material appears at high risk and the other causes are at moderate risk group.

Eratak (2014) conducted a study utilizing regression, neural network, and fuzzy logic in order to investigate accident severity estimation models, according to workday losses. In the study, 14 years of accident data from Turkish Coal Enterprise (TKİ) and 4 years of accident data from TTK mines were used. Eratak (2014) discussed the variables age, season, time, cause, and affected part of the body by the three methods given. It appear that, for instance, age parameter can be considered to have a weak or negligible effect, similar with season. First shift (08.00-16.00) was detected as responsible for enhancing the severity of accidents. While manual handling is the most significant accident type in lignite mines, blasting and gas/dust explosions take place in hard coal mines (Eratak, 2014).

2.4.1 Fault Tree Analysis (FTA) and Applications in Engineering

System safety engineering is based on three concepts that 1) an accident is the result of a number of interacting causes within a system, 2) each cause and interaction can be logically identified and evaluated, and 3) solutions can be developed to control each cause (Brown, 1993). These three steps are also the major features of FTA. Roland and Moriarty (1983) specified FTA as a form of hazard analysis used to analyze a single catastrophic event such as, a methane explosion, that could occur within a defined system.

Understanding and correcting how they can go wrong is a significant requirement for designing systems that work properly. FTA is the most commonly used technique for causal analysis in risk and reliability studies (Rausand, 2004). International Crisis Management Association (ICMA, 2014) indicated that, fault trees provide a good framework for both qualitative and quantitative analysis because they have both logical (Boolean algebra) and probabilistic basis. A fault tree diagram follows a top-down structure and represents a graphical model of the pathways within a system that can lead to a foreseeable, undesirable loss event or a failure. It contributes to the major effort of this study, to find the root causes of mining accidents and fatalities.

Moraru and Babut (2013) indicated that FTA was the first method designed to achieve a systematic review of industrial risk. H. Watson of Bell Labs, along with A. Mearns, developed the technique for the Air Force for evaluation of the Minuteman Launch Control System, circa 1961. Later on, it was recognized by Dave Haasl of Boeing as a significant system safety analysis tool (Ericson, 1999). The first major use of FTA was the application by Boeing on the entire Minuteman system for safety evaluation (1964-1967 and 1968-1999). The initial technical papers on FTA were presented at the first System Safety Conference, held in Seattle, June 1965. Afterwards, the technique was adopted by the aerospace, nuclear power, and chemical industry. Especially throughout 1990’s, computer softwares were developed and the utilization became widespread (ICMA, 2014).

Fault tree diagrams consist of gates and events connected with lines. The *AND* and *OR* gates are the two most commonly used gates in a fault tree. To illustrate the use of these gates, consider two events, input events, that can lead to another event, the output event. If the occurrence of either input event causes the output event to occur, then these input events are connected using an *OR* gate. Alternatively, if both input events must occur in order for the output event to occur, then they are connected by an *AND* gate. Table 2.7 indicates the FTA symbology with the summarized meanings.

Table 2.7 The symbols used in FTA (Smartdraw, 2015)

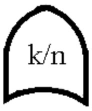
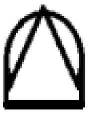
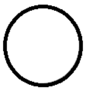
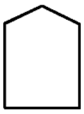
Symbol	**Name**	**Meaning**
	AND Gate	The output event occurs if all input events occur
	OR Gate	The output event occurs if at least one of the input events occurs
	VOTING Gate	The output event occurs if k or more of the input events occur among n events
	INHIBIT Gate	The output event occurs if all input events occur and an additional conditional event occurs
	PRIORITY AND Gate	The output event occurs if all input events occur in a specific sequence
	EXCLUSIVE OR Gate	The output event occurs if exactly one input event occurs
	EVENT	The top event to be analyzed
	CONDITIONAL Event	A specific condition or restriction that can apply to any gate
	BASIC Event	A basic initiating event for the failure
	HOUSE Event	An event that is normally expected to occur. In general these events can be set to occur or not to occur, they have a fixed probability of 0 or 1

Table 2.7 The symbols used in FTA (Smartdraw, 2015) (Continued)

Symbol	Name	Meaning
◇	UNDEVELOPED Event	An event which is no further developed. It is a basic event that does not need further resolution
△	TRANSFER Symbol	Indicates a transfer continuation to a subtree

Qualitative analysis evaluates a fault tree in terms of its minimal cutsets, common mode failures and importance of components that may lead to an unwanted situation. Quantitative analysis of a fault tree helps to estimate the probability of an event from the given failure probabilities of the system's components and basic causes (Vesely *et al*., 1981). National Aeronautics and Space Administration (NASA, 2002) suggested eight steps to be considered in FTA: (i) identify the objective of FTA, (ii) define the top event of FTA, (iii) define the scope of FTA; (iv) define the resolution of FTA; (v) define ground rules of FTA, (vi) construct the tree; (vii) evaluate FTA; and (viii) interpret and present the results (Zhang *et al*., 2014). In this manner, advantages of FTA can be briefly listed as:

- It directs the analyst to ferret out failures deductively,
- It points out the aspects of the system which is appropriate for an understanding of the mechanism of likely failure,
- It provides a graphical assistance enabling those responsible for system management to visualize the hazard; such persons are otherwise not associated with system design changes,
- Providing a line of approach for system reliability analysis (qualitative and quantitative),
- Allowing the analyst to give attention to one particular system failure at a time,
- Providing the analyst with genuine understandings into system behaviour, and
- Enabling human and other non-hardware failure causes to be evaluated.

Besides the mentioned advantages, FTA has also some drawbacks, such as focusing only on one particular type of problem in a system (multiple fault trees are required to address the multiple modes of failure), requiring a skilled analyst, and being an expensive and time-consuming risk analysis.

The prediction accuracy of FTA depends on the precision of component failure data. Ideally, failure probability of the top-event is calculated by considering failure probability data of the basic components of a system to be exact values. However, in practice, ambiguity of system and component behavior, the working environment of a system, and a lack of sufficient statistical inference raises difficulties during estimation of exact failure probability of basic components (Ferdous *et al*., 2009).

Cut sets are sets of components that, when they occur, will cause a top fault event. A minimal cut set is a set of events that, if any event were removed from that set, would not generate a top fault event. This information helps to identify failure events whose exclusion secures the system and directing efforts to prevent a top fault event (Ortmeier and Schellhorn, 2007).

2.4.2 Previous Studies on Risk Assessment of Methane Explosions

Before FTA of methane explosions, some other examples of FTA used in other industries are examined in order to understand the mechanism of fault tree construction and outcome. For example, Moraru and Babut (2013) used FTA for the water supply system of an industrial facility. The environment consists of a tank (R_1), hand valves (V_1 and V_2), electric pumps (P_1 and P_2), and clapper valves (C_1 and C_2) that utilized in order to supply the given Q water quantity to the system SA. Top event of the fault tree is system SA not fed. The second level of the fault tree consists of downstream of C_1 and downstream of C_2, which are connected with *AND* gate to the top event. Resolving to basic events follow the same manner with $P_{1,2}$ and $V_{1,2}$. Basic events of the tree appear as $V_{1,2}$ blocked, $V_{1,2}$ not opened, tank R_1 empty, and loss of electric power for $P_{1,2}$. The case study indicated by Moraru and Babut (2013) is one of the most common examples of a basic fault tree, examining the failures in the system consisting a tank, valves, pumps, and finally the supply system has to be fed.

Iverson *et al*. (2001) used FTA in order to investigate one of the recurring surface mining safety problems – a dozer falling into a void over a drawpoint on a coal surge pile. Besides identifying basic and intermediate events that led to the accident, a sensitivity analysis showed which events had the greatest influence on dozer burial. The two secondary fault events, void formed inside pile above feeder and bulldozer positioned on coal over feeder, are connected by *AND* gate to the top event, bulldozer falls through bridged void. After resolving the intermediate events, finally the major basic events of the fault tree were related to high precipitation, processing water, overburden pressure, feeder gate open, operator errors, improperly operating conveyor, poor weather conditions and inadequate training. Zhou (2013) constructed a fault tree of coal mine fire accidents. The basic events of the fault tree were smoking, electrical welding, open flame, setting fire, operating with power on, dissambling safety lamps, static sparks, ill operation of machinery, blasting, using non-flameproof equipment, faulty wire connection, belt friction, and invalid junction box as the ignition source.

Direk (2015) conducted a fault tree analysis whose top event was roof and rib fall injuries. In the study, top event was resolved into three; engineering/supervisor error, management error, and human error, as the secondary faults. These secondary faults were connected to the top event by 2/3 voting gate, which means that unless two of the three faults happen at the same time, there will not be any roof and rib fall injuries. Engineering/supervisor error was further resolved to ineffective inspections/controls and support design error. Management error was further resolved to inadequate training, improper equipment, inadequate planning, and insufficient working conditions. Human error was further resolved to unsafe act and unsafe condition. Fault tree has 39 basic events, 8 of which were identified as undeveloped events. Most frequent events were found as insufficient risk assessment (10.97%), improper additional roof supports (9.95%), poor safety culture (9.26%), and failure to control preventive safety measures (7.74%). Besides, the highest severity with 11.16% was found as insufficient risk assessment. The mean time of the system was found as 3.73 days with the failure probability of 59.39%. Probability of failure of the system became 100% at 20 days, meaning that in 20 days it is certain that a worker has a roof and rib fall accident. Improper personal protective equipments (PPE) was found as the event with the highest importance. If improper PPE, procedural errors, improper tools, failure to take control measures, and inexperience were assumed to be prevented, the mean time of the system would increase to 6.74 (Direk, 2015).

Davies and Tomasin (1996) suggested a fault tree whose top event is methane explosion. Ignition and methane within explosive limits were the secondary faults and they are connected to the top event by *AND* gate. Ignition fault was resolved to electrical equipment, striking match or smoking, and flame cutting or hot surfaces. Electrical equipment also was resolved to faulty equipment and faulty design. Similarly, methane within explosive limits is resolved to air and methane build-up. Methane seepage and insufficient ventilation were the subfaults of methane build-up and insufficient ventilation is resolved as ventilation failure and faulty design. No further resolution of fault events to basic events was given in the study.

Fan *et al.* (2011) also conducted another study whose main concern was constructing a fault tree with the top event of methane explosion. At the beginning of the study, the safety input to prevent explosions was divided into two, namely engineering physical input and human behavior input. While the first one means to eliminate unsafe factors, make production process, mechanical equipments, and other production conditions safe, human behavior input refers to use of education, training, implementations of safety management rules and regulations to make the production process safe. The main reasons of methane explosion were divided into three; the formation of explosive gas, existing spark origins, and management defects. Fan *et* *al.* (2011) indicated that the majority of methane explosions in coal mines is because the staffs' violating operation.

> "*Many of the coal mine workers are low degree of culture, and they do not accept formal safety training well. Workers' safety consciousness are weak, they often use the way of "teacher led the disciple" in mining operations, they are lack of basic knowledge about safety production, they do not understand ventilation safety managements and operating rules, and they have seriously phenomenon, such as thought paralysis, against the rules and adventure foolhardy"* (Fan *et al.*, 2011).

In the study, the explosive gas and spark origin were connected to the top event, methane explosion, by *AND* gate. Later on, the explosive gas was resolved to power failure, insufficient wind, not ventilation in time, and gas leak. Similarly, spark origin was resolved to smoking, miner's use, blasting flame, high-powered light bulbs, strike sparks and friction sparks, and electrical fire. No further resolution of fault events to basic events was given in the study (Figure 2.2). The approach of the study does not coincide with OSH perception in developed countries due to its level of worker blaming. The effect of human error in occupational accidents is unnegligible, as discussed in Chapter 2.2.2, but the features like having low degree of culture, not accepting formal safety training or lack of basic knowledge about safety production are relevant to the duties of the employer and administrative structure. After all, the main concern behind starting to work trainings, periodical trainings, and emergency drills is solving the mentioned problems. The successful countries in OSH also do not have completely sophisticated and high-educated coal miners but the internal auditing system is settled within the companies.

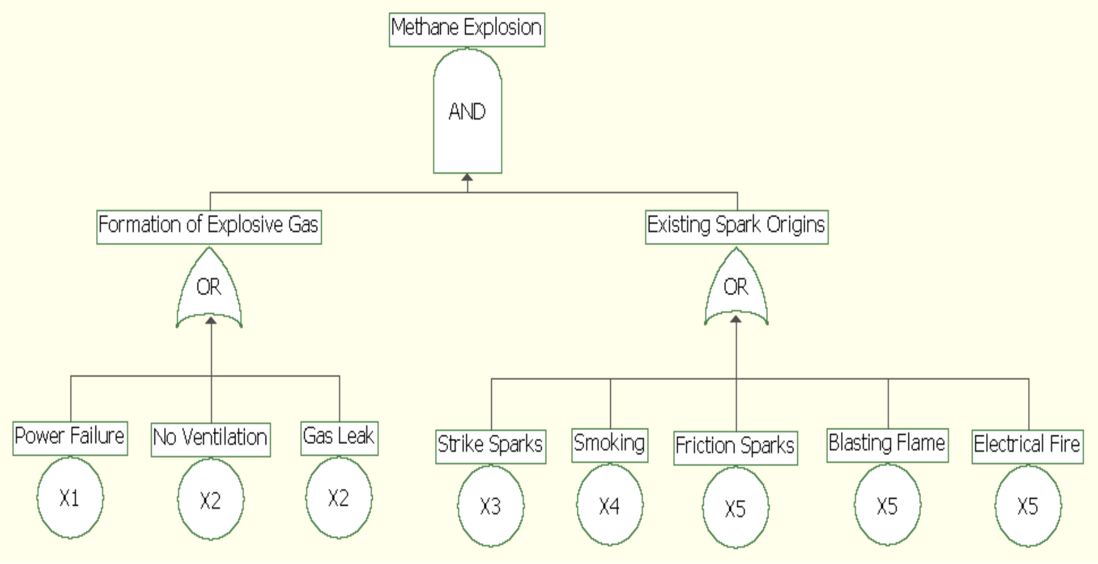


Figure 2.2 Fault tree of methane explosions by Fan *et al.* (2011)

Rankin and Tolley (1978) suggested a fault tree for methane explosion, whose primary events are excess methane and ignition source and connected to the top event with *AND* gate. Besides, air is specified as a *house event*. Excess methane is divided to the *undeveloped events* of high mining rates and moderate ventilation. Similarly, ignition source is divided into *undeveloped events* of open flames, electrical defect and mechanical spark. All of the *undeveloped events* are connected to the primary events with *OR* Gates (Figure 2.3).

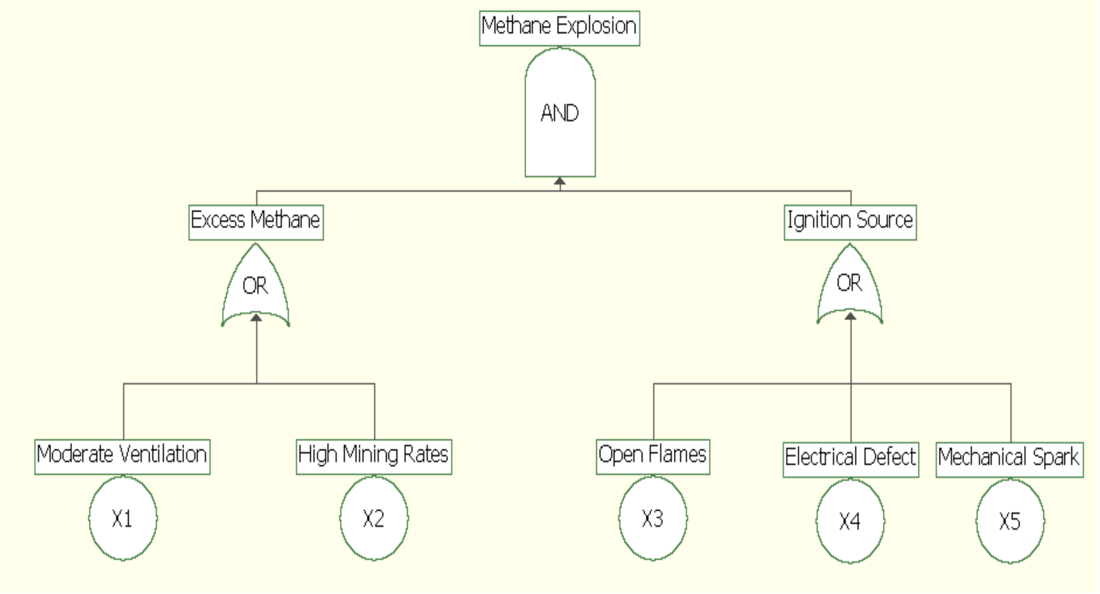


Figure 2.3 Fault tree of methane explosions by Rankin and Tolley (1978)

Coal Services Health and Safety Trust (2007) in Australia constructed a fault tree that consists of again the flammable gas and ignition source connected by *AND* gate to the top event methane explosion, and resolved flammable gas to gas emission, inadeqaute ventilation, and outburst, while resolving ignition source to spontaneous combustion, electrical spark/arc, and mechanical sparking. Gas emission was also resolved to stoppings and seals. Similarly, inadeqaute ventilation’s basic events were ventilation tubes not up to face and inadequate fan speed. On the other branch of the tree, electrical spark/arc was resolved to faulty installation and faulty equipment.

Doyle (2001) represented a qualitative fault tree analysis of methane explosion. The scope of the analysis was tunnel engineering and the explosions possible to occur in construction tunnels. Therefore, the instersection with a coal-bearing strata during tunnel boring, which was qualified as a slight probability in the study, was considered. Doyle (2001) focused on the possible deficiencies on the air ducts inside tunnel. It was indicated that pinched or obstructed air ducts may result in high duct resistance and deficient duct flow, and finally an impaired ventilation system. Also, failed fans result in an inoperative ventilation system and these two cause a combustible atmosphere in the tunnel. Doyle (2001) classified the ignition sources as open flames, static sparks, electrical arc or sparks, and friction sparks or hot surface. No further resolution of fault events to basic events was given in the study (Figure 2.4).

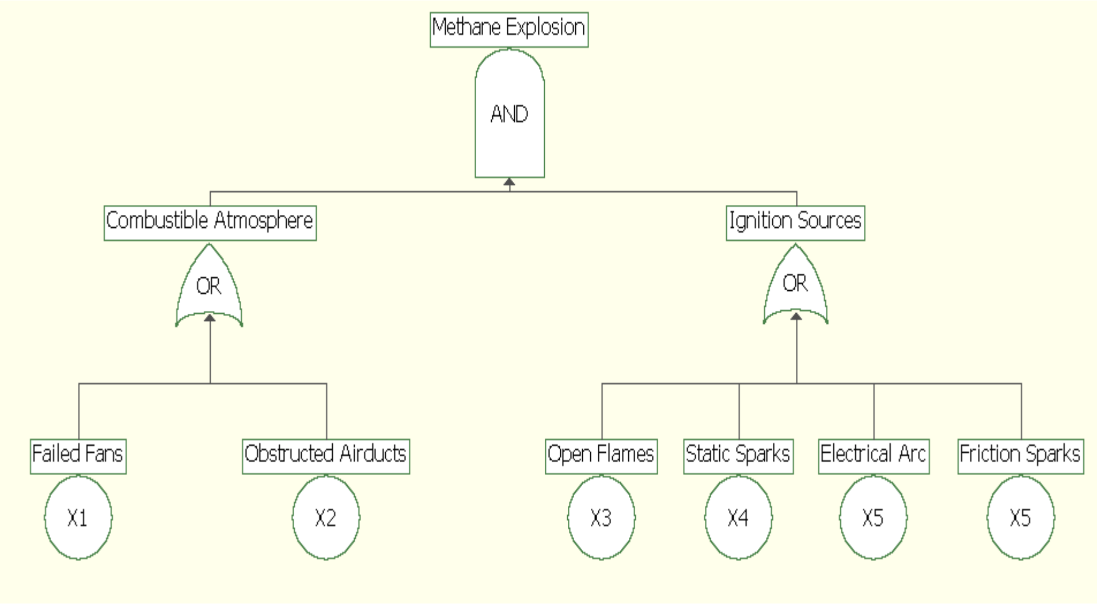


Figure 2.4 Fault tree of methane explosions by Doyle (2001)

2.5 Rationale of the Study

Analyzing risks by deduction concept will be a useful decision for industries placed in very dangerous class as mining. It is advantageous for identifying and evaluating the hazards causing unwanted failures. Therefore, FTA was used in this study. The technique does not have a common use in Turkish mining industry at the present time. Gradually, the companies should become familiar with that type of computer softwares to talk about an improvement in occupational safety and health level of the country. Risk reduction studies using fault-tree analysis have shown that large reductions in explosion risk only result from multiple preventive actions. For example, a ventilation upgrade or a methane monitor upgrade by itself offers risk reductions under 50%. A risk reduction of 90% or more would typically require much more thorough gas checks during welding. Other studies have shown that the everyday vigilance of those working underground is as important as engineering design (Kissell *et al*., 2007).

Fault tree is constructed by deductive reasoning from the principal undesirable event, or *TOP* event, down through intermediate causation events, to basic events that cannot be subdivided further. At each step in the process the analyst asks "How can this occur?" (Doyle, 2001). There is no unique way to represent a fault tree (Caceres and Henley, 1976). Best results are obtained when personnel skilled in various aspects of the system are involved in constructing the tree, such as, the ventilation specialist, the electrician, safety personnel, maintenance personnel, and management. Capturing the experience and diversity required for identifying site specific conditions and controls, thus obtaining the best possible outcome in terms of risk management. Any fault tree constructed is open to comment and may be evaluated variously from different point of views.

The examples of constructed fault trees for methane explosions mentioned in Section 2.4.2 reveal that, the intermediate events and basic events are similar to each other and the fault trees have generally two or three steps between the top event and basic events. It means that the studies have a simple approach and insufficient at resolving the faults of the system in detail. In this study, a comprehensive fault tree of methane explosions is conducted. Moreover, FTA studies in Turkish mining industry, especially dealing with methane explosions, have a limited availability and it is an important gap considering the essentiality of risk analysis for a sustainable OSH progress in mining industry. This study will also be an introduction for further risk analysis studies in the country. Risk analysis methods other than 5 x 5 matrix technique should be adapted to Turkish mining industry and developed continuously.

CHAPTER 3

DATA AND STUDY AREA

3.1 Research Area

Zonguldak hard coal field is the first location where hard coal was found and started to be extracted in Turkey (TTK, 2013). The field is surrounded by Kastamonu from the east, Çankırı from the southeast, Bolu from the south and Black Sea from the northwest. The basin is 340 km from İstanbul and 275 km from the capital, Ankara. The field had came out nearly 270 million years ago as a result of the coalification process in the carboniferous period. The field has got a very faulted geological structure. Coal seams are gaseous and prone to fire and inrush incidents. The production is labor intensive due to the depth of production, complicated geological structure and dip of the coal seams in the field, which makes fully mechanized production difficult to implement (TTK, 2013).

The management operating at the field was named as Turkish Hardcoal Enterprises (Türkiye Taşkömürü Kurumu, TTK) in 11.04.1983 by the 60th statutory decree (TTK, 2013). Today, the production continues in five enterprises, namely, Amasra, Armutçuk, Karadon, Kozlu, and Üzülmez (Figure 3.1). Since 1848, the beginning of production at the field, nearly 400 million tonnes of marketable hard coal has been produced (TTK, 2013). The maximum production rate of raw coal in the history of field reached to 8.5 million tonnes in 1974. In the same way, the maximum production rate of marketable coal was reached to 5 million tonnes in 1967 and 1974. After 1974, the production rates started to follow a decreasing trend and dropped to 4 million tonnes around 1982. Today, TTK is the leading hard coal mining company in Turkey with its average 2 million tonnes of marketable hard coal production annually

(TTK, 2013). TTK also works in collaboration with some foreign countries' coal mining institutions such as, Germany, Ukraine, and Poland. Private sector companies run 93% of coal and lignite mining in Turkey. The rest are public institutions, including TTK.

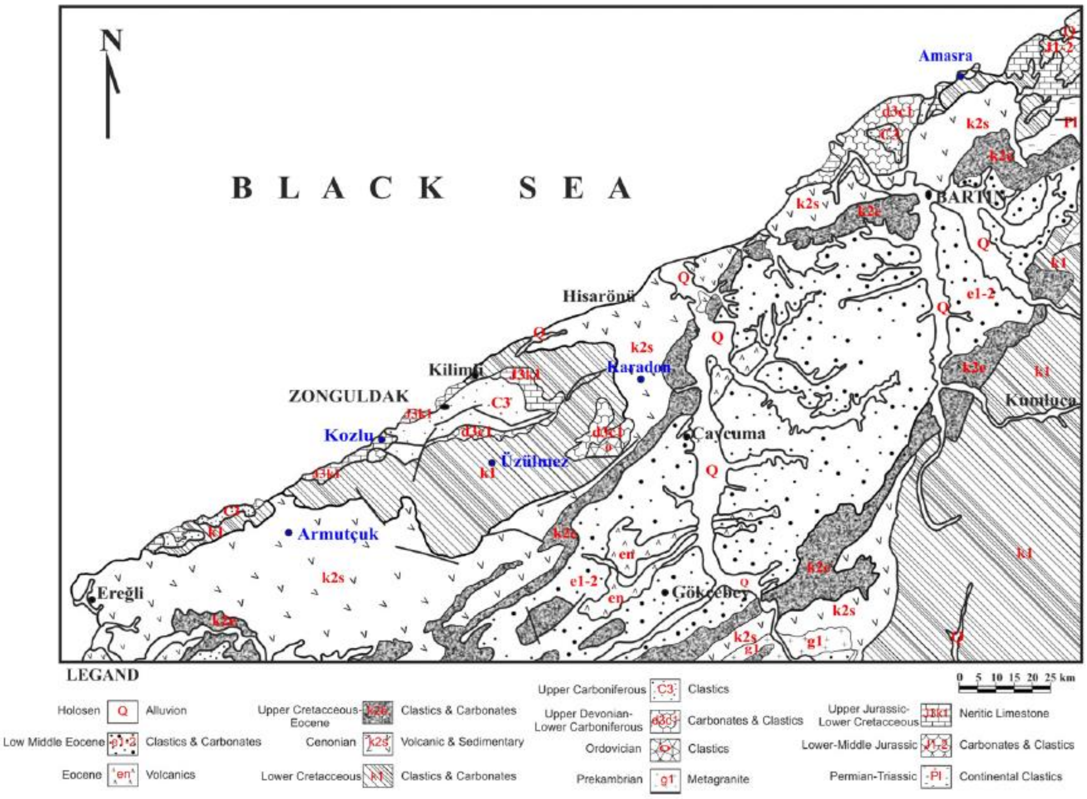


Figure 3.1 Geological map of Zonguldak coal field and five TTK Enterprises (Buzkan, 2008)

The thickness and the dip of approximately 20 coal seams within TTK are variable and the production proceeds between the levels +155 and -550. On average, production proceeds at the level -320. Considering 2013, coal seam characteristics of these five enterprises are given in Table 3.1. Having an average thickness of 6 m and 4.5 m, respectively, the most important coal seams in the basin are Çay and Acılık. Moreover, Sulu, Hacımemiş, Domuzcu, and Büyük seams are also regarded as important for coal production. These seams have an average thickness ranging from

1.5 m to 2.5 m (Baris, 2013). The panel lengths given in Table 3.1 represent the total lengths considering all the panels in each enterprise. For example, Karadon has got eight active panels considering March 2015 and the summation of those eight panel lengths gives 2408 m.

Table 3.1 Coal seam characteristics of TTK Enterprises (TTK, 2013)

Enterprise	**Surface Level**	**Bottom Level**	**Dip Angle (°)**	**Panel Length (m)**	**Coal Seam Thickness (m)**
Armutçuk	-450	-550	13	428	2.67
Amasra	-40	-300	34	202	2.79
Üzülmez	-7	-220	11	1017	2.30
Karadon	0	-490	36	2408	2.56
Kozlu	-400	-560	39	324	2.23

Much of Turkey’s coal is low-quality lignite. In 2010, total of 71.8 million tons of coal was produced in Turkey, 3.7 million tons of which as hard coal and 68.1 million tons of which as lignite (Baris, 2013). Coal represents about 20.8% of Turkey’s total power generation, with lignite comprising 66% of that (Euracoal, 2007). Hard coal reserves of Turkey are only available in Zonguldak coal basin. The hard coal reserves according to five enterprises separately are given in Table 3.2. Proven hard coal reserve of Zonguldak basin, and also of the country, is 1.31 billion tons (Baris, 2013).

Table 3.2 Hard coal reserves (million tons) in Zonguldak basin, considering five enterprises (TTK, 2013)

Reserve Type	**Amasra**	**Armutçuk**	**Kozlu**	**Üzülmez**	**Karadon**	**TOTAL**
Ready	0.4	1.1	2.4	1.4	5.6	10.9
Proven	170.8	9.0	67.7	136.1	131.5	515.1
Probable	115.1	15.9	40.5	94.3	159.2	425.0
Possible	121.5	7.9	48.0	74.0	117.0	368.4
TOTAL	**407.8**	**33.9**	**158.6**	**305.8**	**413.3**	**1,319.4**

3.2 Data Collection and Processing

The research is conducted considering the whole basin including five enterprises. Private subcontractor companies working the seams at TTK’s royalty fields are excluded. Since 24.10.1985, occupational safety and health issue within TTK has been carried out by the Department of Occupational Health, Safety and Training (TTK, 2013). The Department keeps the accident records of the whole basin and performs prevention measures, including the management of risk analysis. Accident data from 1875 to 2014 were obtained from the Department. Risk analysis of the enterprises was performed using 5 x 5 matrix method, as discussed in Section 2.4. Although the method represents the conditions in an underground coal mine in general terms, determination and implementation of specific control measures to the mine remain deficient. Probabilities and severities of the failure events are identified and evaluated separately in the risk analysis but their individual effects to the terminal unwanted events such as, methane explosion, mine fires, roof and rib falls, and methane outbursts were not investigated. FTA used in this study eliminates this drawback, as presented in Chapter 4. Between 1875-2014, the recorded fatal methane explosions and other fatal occupational accidents related to methane explosions are given in Appendix. The quantitative FTA presented in Chapter 4 is based on the time between failure rates of this accidents.

3.3 Occupational Accidents in TTK

Zonguldak coalfield is the most dangerous and risky field in Turkish underground coal mining industry and methane explosion is the main cause of fatalities in large numbers. Besides methane explosion, all other types of underground mining problems can be seen in the field such as, methane outbursts, caved ins, inundations, coal dust explosions, mine fires, material handling and transportation accidents *etc.* and also occupational diseases such as, pneumoconiosis.

Number of total fatalities irrespective of the cause between 1875-2014 in TTK are given in Figure 3.2 considering five enterprises separately. Kozlu has the highest fatality rate in this time interval. Miscellaneous column on the figure represents the fatalities occured in Head Office, surface installations, traffic accidents or undefined locations.

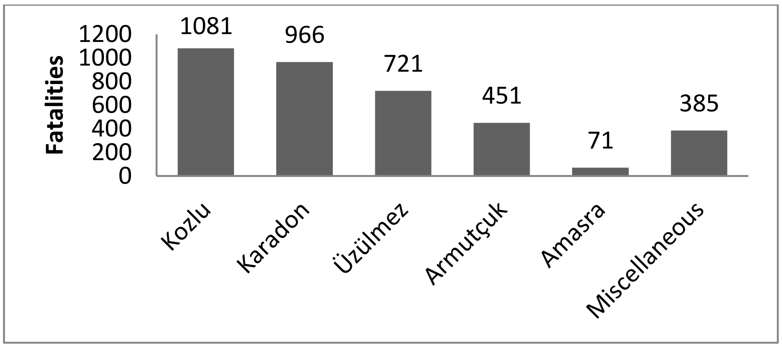


Figure 3.2 Fatalities between 1875-2014 in TTK Enterprises (TTK, 2015)

Besides these five Enterprises, TTK also have the royalty of many fields in Zonguldak where the private subcontractor companies operating the coal seams. Similarly, accident statistics of that private companies reveals the risk level of the basin. Figure 3.3 combines the fatality rates of TTK and private sector companies in Zonguldak basin between 2000-2013. It appears that the most number of fatalities were recorded in 2008 (26 fatalities in total). The reliability of data is uncertain due to the absence of an efficient record keeping and also some undeclared operating persons in the field. Expanding the time interval from 2000-2013 to 1992-2012, there were 269 recorded occupational accident fatalities and methane explosion was the cause of 29 fatalities, taking the share of 11% of overall (TTK, 2015).

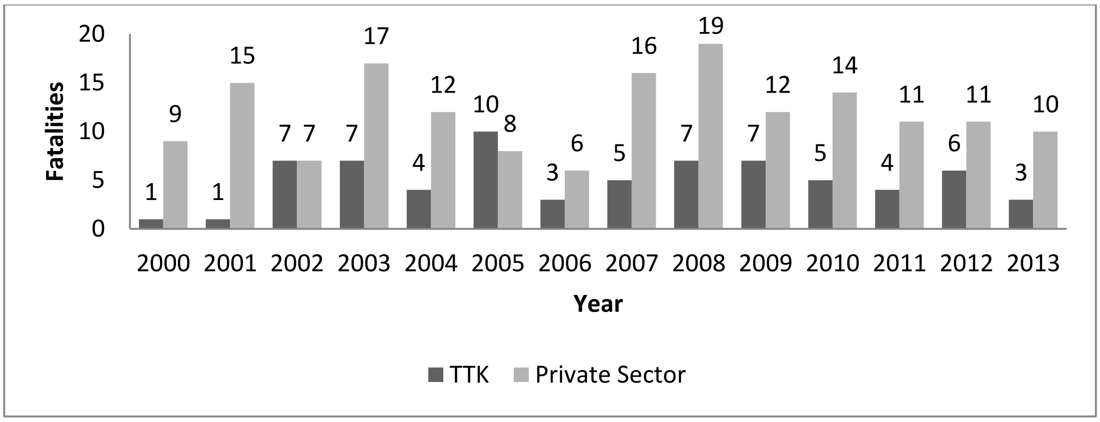


Figure 3.3 Fatalities in TTK and private sector in Zonguldak between 2000-2013 (TTK, 2015)

3.4 Methane Explosions in TTK

According to acquired data, 67 different methane explosions were resulted in 815 fatalities (22%) between 1875-2014. Most probably, the data is not precise due to the level of OSH concern at especially 19th and early 20th century and record keeping habit. Focusing on methane explosion, five disasters resulted in the most number of fatalities in Turkish mining industry are given in Table 3.3. It is a remarkable fact that four of the accidents have occured in TTK. Most recently, in 17.05.2010, another methane explosion resulted in 30 fatalities at Karadon. Table 3.3 also underlines a crucial fact that, the biggest explosions have happened in the past 30 years.

Table 3.3 Five explosions resulted in the most number of fatalities in Turkish underground coal mining industry (TTK, 2015)

Name of the Enterprise	Date	Fatalities	Annual Production (ton)
Kozlu	03.03.1992	263	947,820
Armutçuk	07.03.1983	103	444,940
Amasya	07.02.1990	68	
Armutçuk	03.12.1942	63	268,823
Kozlu	21.09.1947	48	893,889

Total of 815 fatalities due to 67 different methane explosions are specified considering five enterprises separately between 1875-2014 (Table 3.4). Kozlu has the biggest share with 53% of overall and appears as the most fatal enterprise. This result mostly depends on the second largest mining disaster in Turkey, following Soma 2014, which took place at Kozlu in 1992 with 263 fatalities. Armutçuk follows Kozlu with 27% share.

Table 3.4 Fatalities due to methane explosions within TTK between 1875-2014 (TTK, 2015)

Name of the Enterprise	Fatalities	Percentage (%)
Kozlu	434	53
Armutçuk	219	27
Karadon	137	17
Üzülmez	19	2
Amasra	6	1
TOTAL	**815**	**100**

CHAPTER 4

QUALITATIVE AND QUANTITATIVE FAULT TREE ANALYSIS

4.1 General Information

In this study, qualitative and quantitative fault tree analysis of methane explosions in underground coal mines are carried out separately, considering accidents occured between 1875-2014 within five TTK Enterprises. In order to construct the fault tree, three site visits were arranged to Zonguldak – one in 2014 and two in 2015. Observations during these site visits contribute directly to the generation of fault tree. During the visit in March 2015, a meeting was organized at Department of Occupational Health, Safety and Training within TTK. Zonguldak coal field's occupational accident data was obtained during the meeting. Data do not include the explanations or comments related to methane explosions happened, which is one of the major deficiencies of country's OSH status. It involves just descriptive statistics of occupational accidents with date of the accident, occupation of the accident victim, age of the victim, location of the accident, type of the accident, and short descriptions of some accidents starting from 1965. Besides the data obtained from TTK, Labor Inspection Board's (2014) annual reports of mining industry had also contributed the construction of the fault tree. These reports include the stated deficiencies in underground coal mines and their statistical records starting from 2011. The deficiencies identified in five TTK enterprises were examined and compared to the observations made during the site investigations. Therefore, accident data obtained from TTK, site investigations, and annual evaluation reports of Labor Inspection Board assisted the determination of fault tree components.

4.2 Qualitative Fault Tree Analysis of Methane Explosions

The *top event* of the fault tree is specified as “Methane Explosion” considering underground coal mines. There are 3 major events (combustible atmosphere, oxygen supply, and source of ignition), 27 intermediate events, and 65 basic events constituted on the fault tree. Such a detailed fault tree of methane explosions is presented for the first time. The three essential conditions, namely the major events, generating an explosion are connected with *AND* gate to the *top event* (Figure 4.1). Some of the intermediate events are presented as subdiagrams in order to arrange the simplicity of the tree’s appearance. The subdiagrams are resolved to their basic events and detailed explanations are given in the following sections of the chapter. Oxygen supply is represented as a *house event* on the fault tree, as it is a normally expected atmospheric condition and satisfied naturally – it is generally greater than 20% in ordinary mine ventilation. It is a normally expected event to occur which has the fixed probability of 1 as it was mentioned in Chapter 2. Therefore, suppressing explosive methane presence (combustible atmosphere) in the environment and removing any kind of ignition source in the mine become the main objectives of prevention strategies against methane explosion. However, adequate ventilation may not be the only solution against methane existence. To set an example, outburst incidents also cause serious amounts of methane outcome from the face as indicated in Chapter 2. In the following section, generation of a combustible atmosphere in an underground mine will be discussed via the fault tree.

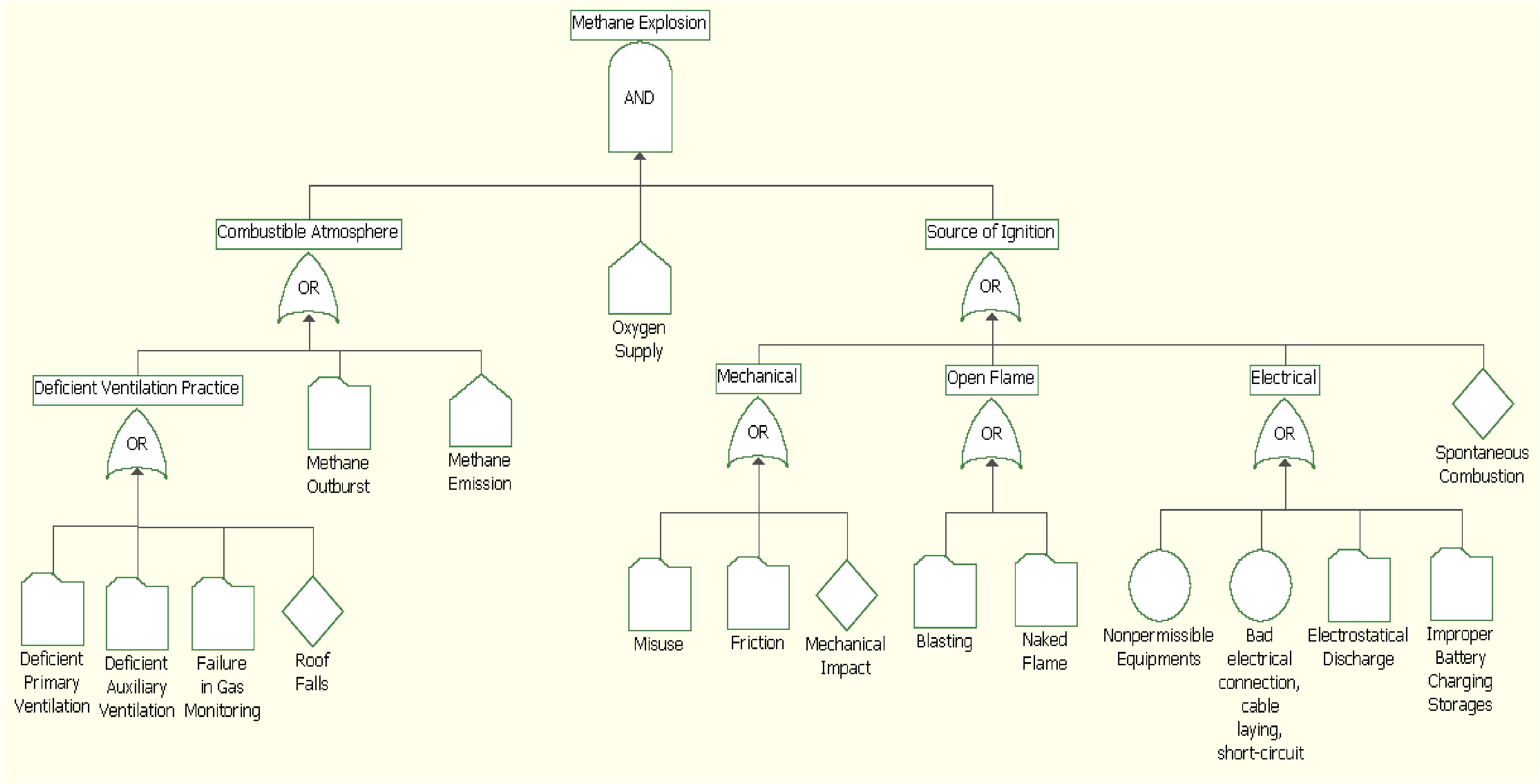


Figure 4.1 Qualitative fault tree of methane explosion

4.2.1 Combustible Atmosphere

Explosive methane concentration may be a result of methane emission (from coal seam and surrounding strata), deficient ventilation practice in the mine, and sudden gas inflows like methane outburst. Methane emission (from coal seam and surrounding strata) is represented as a *house event*, due to the geological and coalification processes occuring naturally, especially considering Zonguldak coal field (Figure 4.1). Here, a contradiction appear for methane drainage. Although it is one of the primary and most efficient practices to reduce the methane amount in the seam and surroundings, it is not qualified as a direct cause of methane accumulation in this study and not specified as a direct *fault* of methane emission (from coal seam and surrounding strata). It is a prevention technique, but also a matter of choice for the company, considering its financial aspects at the same time. A company may have the approach of “having an effective mine ventilation practice without needing methane drainage” during the prevention stages against explosion risk, at least in the countries not obligating the drainage practice by current legislation. However, lack of methane drainage is added on the fault tree, under the intermediate event methane outburst, due to its vital importance. During the construction of the fault tree, the coal mine is assumed as an outburst-prone one.

4.2.1.1 Deficient Ventilation Practice

Mine ventilation can be summarized as the control of air movement, amount, and direction. In order to maintain an effective mine ventilation practice, required engineering studies has to be done starting from preliminary stages. A crucial point about the design of primary ventilation systems is that they must not only meet normal operating conditions but also abnormal conditions, such as in the event of a fire or power outage or other threats. Maintaining a sustainable and correct ventilation in the mine is the major requirement for preventing methane explosions.

Deficient ventilation practice is divided into four groups as (i) deficient primary ventilation, (ii) deficient auxiliary ventilation, (iii) failure in gas monitoring, and (iv) roof falls (as an indirect factor) (Figure 4.1). Deficient primary and auxiliary ventilation practices with failure in gas monitoring are further developed but roof falls are represented as an *undeveloped event*. Caved ins may affect both primary and auxiliary ventilation practices related to their severity, by obstructing the roadways, short-circuit of ventilating air, and damaging ventilation equipments like auxiliary fans. Therefore, it is added as a probable cause of an unavailable ventilation. The three intermediate events are connected by an *OR* gate to deficient ventilation practice. Because a failure at either one of them will affect the efficiency of the whole mine's ventilation. In the following sections, the three intermediate events are investigated separately via their resolutions on the fault tree.

4.2.1.1.1 Deficient Primary Ventilation

Deficient primary ventilation in a mine may be a result of an improper ventilation design or improper primary ventilation fan. As discussed in Chapter 2, ventilation is one of the most important concerns in underground mining and it has to be considered from the preliminary stages. Thus, the design of primary ventilation needs to be achieved carefully. Each ventilation design has its own unique characteristics to be considered separately. It is not only about calculations, but also monitoring and revising the system periodically. In this study, the types of an improper ventilation design are listed as:

- Lack of mechanical ventilation (BE1),
- Reverse ventilation (BE2),
- Ventilation in series circuit (BE3),
- Lack of return airway (for contamined mine air) (BE4),
- Insufficient air quantity (BE5), and
- Short circuit of ventilation.

Mechanical ventilation is an obligation for underground coal mines from both engineering and legal aspects. Lack of mechanical ventilation is a direct cause of methane (or other hazardous gases) accumulation, and also insufficient fresh air for workers. Similarly, reverse ventilation practice may result in insufficient suppression of methane in the mine due to the contradiction between the direction of ventilation and methane's smaller specific gravity comparing to air. Ventilation in series circuit may cause the circulation of contaminated air in the mine. Methane coming from a panel enters to another panel and incorparates into the new contaminated air. Again, it may be a direct cause of an increase in methane concentration in a short span of time. Lack of return airway is a rare situation to see in the mines. Especially in developed mining countries, it is even impossible. However, in some industries, the companies' goal may be focused only on production and extracting the reserve, without considering even the basic OSH requirements. Therefore, lack of return airways of panels or the whole mine itself is included in this fault tree. The purpose of mine ventilation is not only preventing methane explosions, also supplying healthy breathing of the workers. Required amount of air may be classified as required air for breathing and required air for keeping harmful gases below their maximum allowable concentration (MAC) values, namely explosive limits. Required amount of air for breathing is found with respiratory quotient. It is a formula considering the activity of the worker, which affects the air inhaled, and evaluate the quotient for resting, moderate, and vigorous activities. Required air for keeping harmful gases such as, methane, is found by another calculation. The simple approach of the formula is given in Equation 2 (Hartman, 1982).

$$Q = \frac{q}{MAC - b} - q \qquad \text{(Eq. 2)}$$

In Equation 2:

Q: Air required to keep harmful gases below MAC (m^3/min)

q: Gas inflow (m^3/min)

MAC: Maximum allowable concentration (%)

b: Gas concentration in intake air (%)

TTK has 13 primary exhaust fans which exhaust around 54,000 m^3/min from an interval of 300 km and 185 auxiliary forcing fans ventilating 34 km long mine openings (TTK, 2013). In Zonguldak, air quantitities are generally much lower than the ideal values in especially private sector companies. The main reason of this situation is insufficient engineering practice and lack of OSH awareness at top managements. Frequently, mine ventilation is believed to be satisfied by just measuring the methane concentration read by the detector located at the return airway, and if the concentration is below 1%, ventilation is treated as successful, not even paying attention to the required air quantity calculations. Usually, the concern is just obeying national legislation. Intake and return air paths often intersect in the mine. It may result in short-circuit of the system, unless some components are utilized. On the fault tree, short-circuit of ventilation is specified as an intermediate event and resolved into three basic events:

- Improper stoppings (BE6),
- Improper overcast/undercast (BE7), and
- Improper air doors/regulators (BE8).

Stoppings are built to separate and isolate different air courses in underground mines, such as the intake air from the return air or from belt airways. They are permanent walls constructed of brick or other approved materials. Differently, seals are used to isolate worked-out areas of a mine that are no longer ventilated. Overcasts and undercasts are built to allow the two air currents to cross without causing a short-circuit. Undercasts are seldom used unless the roof is unstable as they tend to fill with water or debris, which would slow down the air current. Similarly, mine doors are used to control ventilation in areas of heavy traffic such as main haul roads. The doors are usually hung in pairs to form an airlock, which prevents a change in ventilation when one of the doors is opened. The doors can be manual or automatic. In case they are manual, the closure of the doors has to be carried out rigorously. They have to be hung in such a way that the air pressure will close them if they are left open accidentally. Another type of ventilation control is regulators, which are used to adjust the quantity of air flowing to various sections of the mine. Located in return airways, they are often sliding doors or windows built into permanent stoppings. Last of all, check curtains made of brattice cloth, canvas or plastic, hung across a passageway, but are open to let miners or machinery pass can be used also. They fasten only at the top and deflect intake air into the working area. All of the types of ventilation control are connected with an *OR* gate to the intermediate event short-circuit of ventilation (Figure 4.2).

Besides improper ventilation design, improper primary ventilation fan may be the direct reason of a possible defect on primary ventilation practice. It is one of the most critical equipments used in the whole workplace. Fans may be impracticable as a result of the following ways:

- Lack of spare primary ventilation fan (BE9),
- Lack of automatic activation (of the spare fan) (BE10),
- Lack of warning system (in case of interruptions) (BE11),
- Lack of generation unit (of the fan in case of interruptions) (BE12),
- Lack of automatic activation (of the generation unit) (BE13).

Any kind of mechanical or electrical interruption probability to the primary ventilation fan has to be considered. It brings the obligation of having a spare unit – of both the fan and generation unit – to be activated in case of abnormal conditions. They are connected to the intermediate event improper primary ventilation fan with an *OR* gate. Moreover, these spare units should be activated automatically, not manual. The claim of the management may be holding a worker in charge of the emergency cases around the fan. However, present day OSH approach does not prefer entrusting humans in such critical operations. Because there is always a possibility of human factor contribution in that way. Instead, technology and its advantages should be utilized. Therefore, lack of automatic activation of the spare units of primary fan and generation unit are also added to the tree by using again an *OR* gate as illustrated in Figure 4.2.

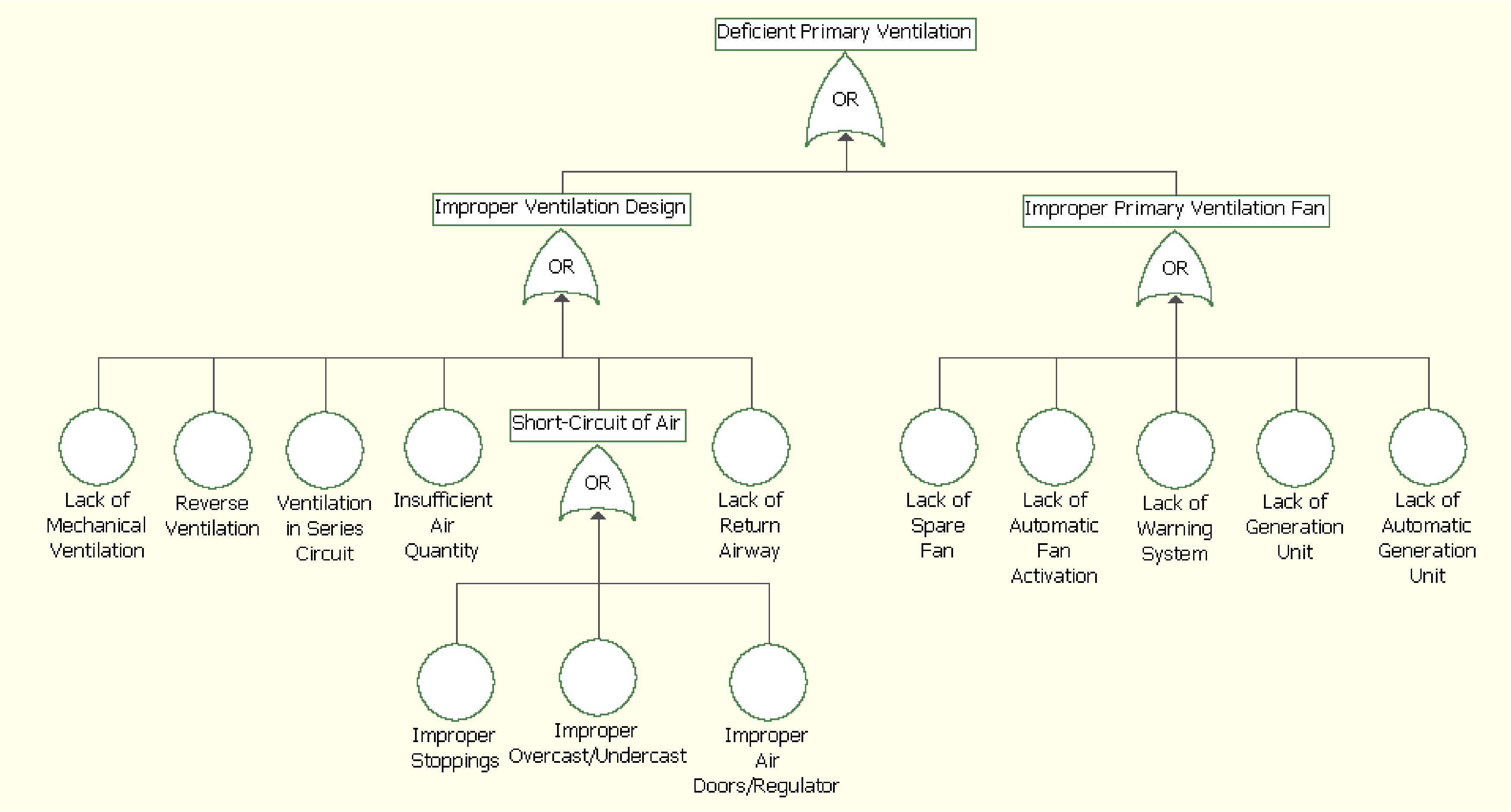


Figure 4.2 Fault tree of deficient primary ventilation

4.2.1.1.2 Deficient Auxiliary Ventilation

The deficiency of the ventilation system may also be a result of the deficient auxiliary ventilation. Auxiliary ventilation is used in order to deliver enough airflow to the headings or blind ends which are not included in the main ventilation network system. It is realized by auxiliary fans and air duct system (Güyagüler and Erdem, 2008). In underground mining, there are three types of auxiliary ventilation: forcing, exhausting, and combination of forced and exhaust systems (Güyagüler and Erdem, 2008). In forcing type of auxiliary ventilation, the flow is directed through the air duct to the working face and the contaminated air returns back from the outside of the duct along the gallery. In general, it is accepted that the auxiliary ventilation should not take more than 40-50% of the air of main ventilation system depending on the through ventilation velocity to prevent recirculation (Güyagüler and Erdem, 2008). In exhausting type of auxiliary ventilation, air is removed from the face and discharged into main ventilation system through the pipe. The suction pressure created by the fan sucks air from the main current. Deficient auxiliary ventilation in a mine may appear as a result of listed circumstances (Figure 4.3):

- Lack of auxiliary ventilation (BE14),
- Arbitrary shut-down of the fans (BE15),
- Airducts far from the face (BE16), and
- Deficiencies on airduct.

Despite the need, there may not be any auxiliary ventilation system established in the mine. It will result in the accumulation of methane at the working faces and also create a suffocating atmosphere to the workers. Presence of the auxiliary ventilation system is not the exact solution. Another issue related to auxiliary ventilation is the arbitrary switching off the fan engine by the workers . It is performed due to the high loudness level of the engine and sometimes feeling cold at the working face because of the ventilating air, as workers tell. It is a frequently seen deficiency especially in private sector companies. The distance between the point of exit of the airduct and the working face is a critical decision and it should not be more than 10 meters in order to satisfy the efficieny of the practice (Güyagüler and Erdem, 2008). Deficiencies on airduct are another affecting factor of the auxiliary ventilation performance. Two major problems related to airduct itself may be listed as (Figure 4.3):

- Undersized airducts (BE17) and
- Leakage (BE18).

In auxiliary ventilation, quality and efficient utilization of the ducting is very important. Ducts may be made of timber, metal, textile or some synthetic materials (Güyagüler and Erdem, 2008). In coal mines, textile and rubberized textile are used. Ducts should be made of flame resistant materials in order to reduce fire, explosion, or poisoning risks, as indicated in the following sections. Besides, the size of the ducts has to be competent in order to satisfy the ventilating air quantity. Air leakage from the ducts should be minimized for securing the sustainable performance of the system. All these failure events are connected to deficient auxiliary ventilation with an *OR* gate as presented in Figure 4.3.

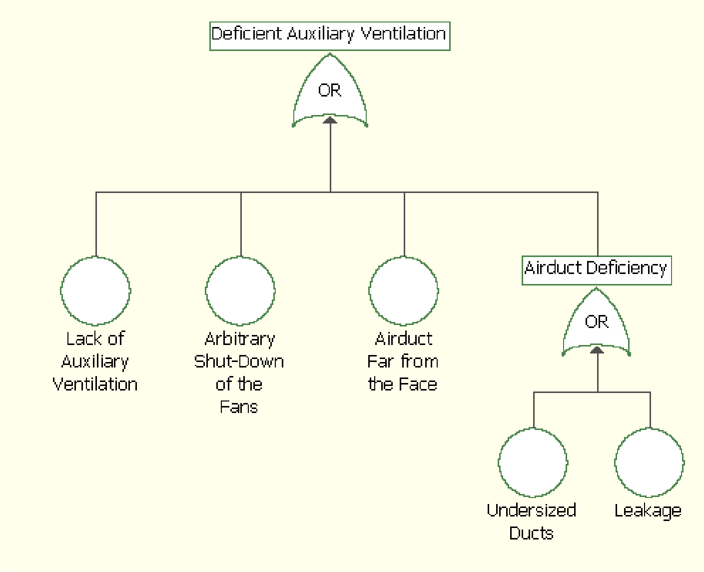


Figure 4.3 Fault tree of deficient auxiliary ventilation

4.2.1.1.3 Failure in Gas Monitoring

Gas monitoring in an underground mine can be performed by stationary or handheld detectors which both should function properly all the time and be used together. Checks for methane are made by certified persons at regular intervals before and during the time while people are working underground. Therefore, the event failure in gas monitoring is divided into two as improper stationary detectors and improper handheld detectors. Deficiencies related to improper stationary detectors are listed as:

- Lack of stationary detectors (BE19),
- Lack of alarming on detectors (B20),
- Incorrect location of detectors (B21), and
- Incomplete gas readings (B22).

Lack of stationary detectors may be the direct cause of a methane explosion. Effective monitoring of underground gas concentrations at surface is a crucial requirement. The connection between subsurface detectors and the surface display unit should be created successfully. In case of interruptions or exceeding maximum allowable gas concentration values, stationary detectors should alarm both subsurface and surface personnel. Moreover, missing sensor types will result in incomplete measuring and also be a problem on an established stationary detector. In Turkish legislation, each stationary detector in the mine have to measure methane, oxygen, carbon monoxide, hydrogen sulphide, temperature, and air velocity (Regulation of Occupational Health and Safety in Mining Workplaces, 2013: Appendix III, Article 10.3). Another obligation related to the subject is the locations of stationary gas detectors. Logically, they have to take measures from critical locations in the mine as return airways. In Turkish legislation, a mine having one panel and one development gallery has to locate the stationary detectors at clean air entrance of the mine, return airway exit of the mine, clean air entrance of the panel, return airway exit of the panel, and return airway exit of the development gallery. Each of the failure events are connected with *OR* gate to failure in gas monitoring.

Handheld detectors are not less important than stationary ones. They are carried by the workers and technical personnel and give instant measurements of the mine atmosphere. Deficiencies related to improper handheld detectors are listed as:

- Lack of calibration (BE23),
- Insufficient amount of detectors (BE24),
- Not measuring abandoned places (BE25), and
- No recording of gas monitoring (BE26).

In general, the devices are not calibrated periodically that results in ineffective measurements. Besides, the number of these detectors are generally insufficient. The recent mining regulation in Turkey obligated each separate team, even consisting of two persons, to carry a detector (Regulation of Occupational Health and Safety in Mining Workplaces, 2013: Appendix III, Article 10.4). Abandoned places and behind the seals are generally ignored by the technical personnel but taking measurements from such places give gas trends and also clues about possible forthcoming problems. Besides, by measuring sealed areas, the possible permeability of the seals can be also detected. Measuring but not recording and commenting on the gas concentration values for different places in the mine is another deficiency. Past measurements are crucial for satisfying a proactive OSH approach. All these four basic events are connected by *OR* gate to improper handheld detectors as can be seen in Figure 4.4.

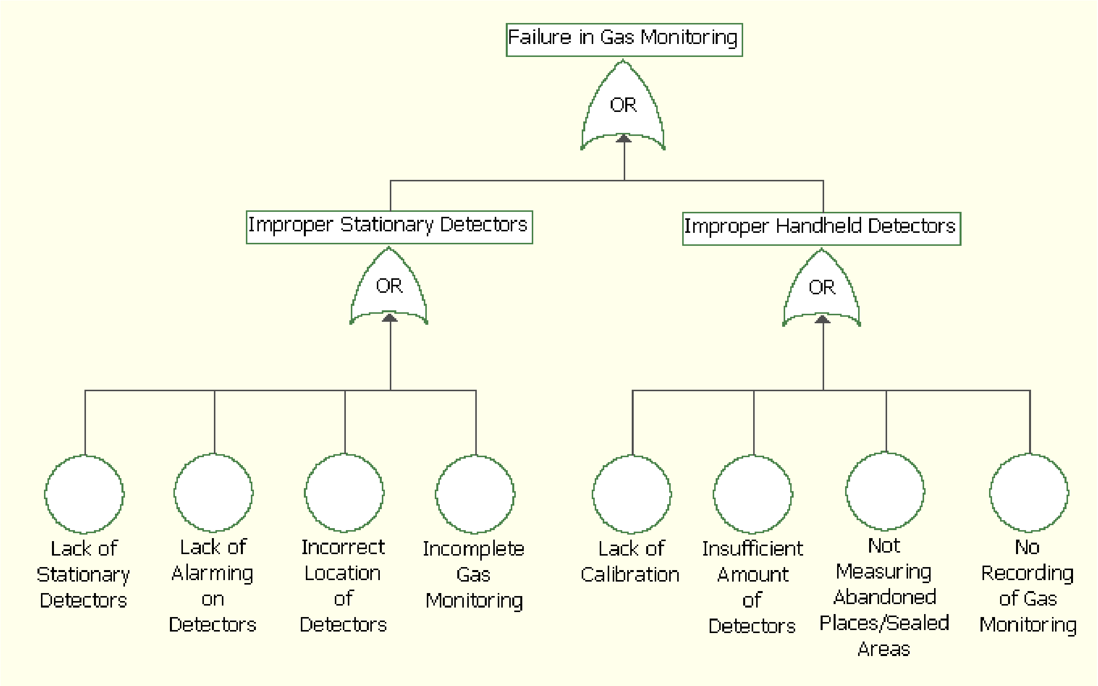


Figure 4.4 Fault tree of failure in gas monitoring

Focusing on Turkish underground coal mining, it is observed that most of mine ventilation problems are related to insufficient investment and engineering practices. The effort of reaching the coal seam by the shortest distance and time results in negligence of required ventilation studies. Inadequate investment capital impels companies and employers to track the coal outcrop. This situation is valid not only for the early stages but also further production stages of the mine. Mineways are mostly timber-supported and constricted in area. It becomes more difficult to supply maintenance of that ways as mines expand. Narrow sections affect both transportation and ventilation practices in a negative way. It results in higher shock losses and higher ventilation resistance, which is a challenging outcome and a high energy-consuming condition for ventilation fans. Also, due to high ventilation resistance, especially for the farthest galleries in the mine, more amount of air has to be sent than the usual and this situation may result in mine fires by triggering spontaneous combustion.

Another result of financial concern stands out as the lack of mechanical ventilation and return airway in coal mines. In underground coal mines, mechanical ventilation practice has to be implemented by both OSH legislation and engineering approach. However, in some small-scaled underground coal mines in Turkey, this requirement is ignored and just natural ventilation is utilized. Moreover, most of the companies applying mechanical ventilation do not have explicit calculations about ventilation resistance, fan characteristics, and ventilation circuit in general. Auxiliary ventilation has to be carried out by completely clean air but it is a frequent practice to utilize ventilation in series circuits and send contaminated air to other galleries. Apart from all these, the worst case about auxiliary ventilation is even not being utilized at most of the mines.

Due to its lower specific gravity (Sp. gr. 0.5537) comparing to air, methane has the characteristics of rising upwards in air, so it settles near the roof of mine galleries. It is the same reason for the requirement of ventilating the mine from the bottom to upper levels. Another problem in Turkish coal mines is sending the contaminated air to lower galleries, which is called reverse ventilation. It results in insufficient ventilation and sudden increase of methane in case of an emergency, such as an interruption at ventilation practice.

In Turkish coal mining industry, a separate mineway for ventilation is not utilized, instead it is carried out on the same way with transportation. Also, in order to prevent short circuit of air in the mine, ventilation doors are used. However, it is difficult to say that the doors are completely leakproof and efficiently governed. For example, generally there is not an automatic closing system and nearly half of the air aspirated by the main fan become short-circuited.

The production method also affects the efficieny of ventilation. For example, retreat longwalling with sublevel caving allows goaf behind the working face and it prevents the leakage of ventilation air. However, room and pillar method is susceptible to air leakage because there exists a lot of underground opening. In hydraulic or pneumatic filling, there is not much ventilation resistance. In underground longwall mining, advance or retreat methods differ from each other that the latter one is more advantegous considering air leakage and ventilation resistance.

4.2.1.2 Methane Outburst

Gas may be found in coal or rock’s constitution or in pores and other blank spaces. Unless an adequate safety pillar has left, the gas may suddenly discharged into the mine openings under high pressure. Gas, coal or coal and gas outbursts together may be seen sometimes. Gas and coal outbursts differ from each other. While most of the gas outbursts are caused by tectonic faults or old production pillars, rock outbursts are caused by high pressure at deep levels in the mine. It results in combustible atmosphere and less than adeqaute (LTA) oxygen concentration which results in asphyxiation.

As discussed in Section 2.3, prediction of a forthcoming outburst is not an easy practice. Observing the significant changes in face conditions may help. Factors such as, ingress of water, changes in stress direction, roof guttering, roof jointing, poor conditions, fluctuations in gas concentrations and gas composition may foretell a coming outburst. Therefore, some precautions has to be taken before working at a specific area in the mine. Methane outburst is divided into two as lack of knowledge and incautious advance. Deficiencies related to lack of knowledge are listed as:

- LTA knowledge about coal gas content, desorption rate, gas pressure (BE27),
- LTA knowledge about old workings (BE28), and
- Outdated mine plans and maps (BE29).

LTA knowledge about coal gas content, desorption rate, gas pressure, or locations and conditions of old workings in the mine may be referred as a direct cause of outburst incidents. Diaz Aguado and Gonzalez Nicieza (2007) indicated that still the mechanisms of gas outbursts are not completely resolved but include the effect of stress, gas content, and properties of the coal. Therefore, determining these parameters is a crucial first step of the methane outburst prevention process. According to Diaz Aguado and Gonzalez Nicieza (2007), in some countries such as, Australia or Germany, a gas outburst risk value has been established when methane concentration exceeds 9 m^3/t. TTK determined the methane content threshold value as 8 m^3/t, which means that the seams containing higher values are referred as outburst prone, while the others are not. LTA knowledge about old workings and outdated mine plans and maps have similar characteristics. These three basic events are connected with *OR* gate to the intermediate event of lack of knowledge.

Zonguldak coal field have been always susceptible to outburst events throughout its mining history. For example, in 1970, the outburst occured in Karadon resulted in 700 tonnes of coal bursted, and in 2004, the outburst occured in Kozlu resulted in 16,000 m^3 of methane emission to the mine (TTK, 2015). Outburst events cause the sudden increase of methane concentration and constitute an explosive atmosphere.

Besides lack of knowledge, incautious advance of the mine workings is another failure event of methane outburst, the basic events of which are:

- Lack of methane drainage (BE30),
- Lack of/Improper check borings (BE31),
- Lack of/Improper safety pillar (BE32), and
- Lack of water injection (BE33).

Lack of methane drainage is added on the fault tree under methane outburst, as explained in Section 4.1. The legislative change in Occupational Safety and Health in Mining Regulation on March 10, 2015 has more extended methane outburst provisions than before. Three parameters are determined for evaluating the outburst risk in a mine: 1) Gas content of the coal seam, 2) Desorption capacity of the coal, and 3) A scientific assessment of gas emission by considering the inferences of (1) and (2). If the mine is not found as an outburst-prone one, regular gas monitoring will be enough. However, if it is found as an outburst-prone coal mine, the numerical limit value of coal gas content for this decision is not specified in the Regulation, one of the three precautions have to be taken: 1) Methane drainage, 2) Leaving a safety pillar not less than 50 m, and 3) Advancing with check borings. Length of the check borings has to be at least 25 m. After each 10 m-advance, borings should be repeated (leaving a 15 m-safety pillar). Regulation obligates employers to drill at least four different-directioned borings when coming close to formerly worked galleries and crossing a coal seam or a fault (Regulation of Occupational Health and Safety in Mining Workplaces, 2013: Appendix III, Article 12.5). Chen and Cheng (2015) found that methane desorption quantity gradually decreased with the amount of injected water. It can reduce the outburst events by impacting on the methane desorption quantity, methane desorption velocity, and methane diffusion coefficient. The four basic events are connected with *OR* gate to incautious advance. However, incautious advance and lack of knowledge are connected with *AND* gate to methane outburst because they have to occur at the same time in order to cause a possible methane outburst (Figure 4.5).

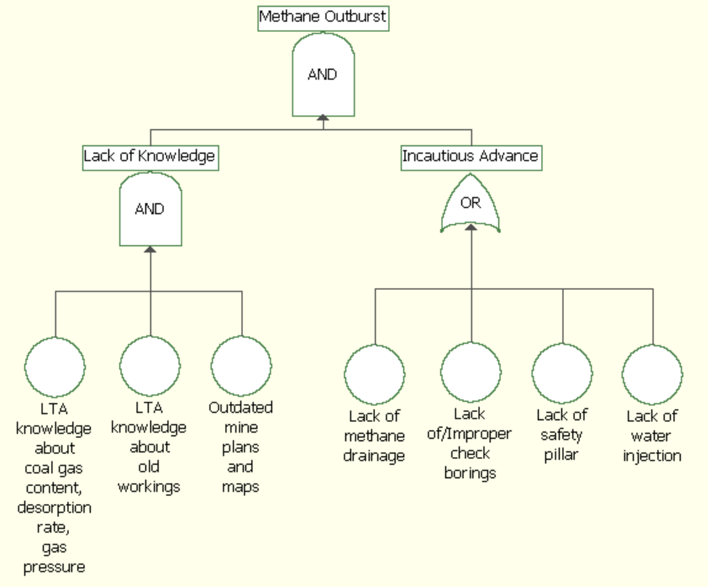


Figure 4.5 Fault tree of methane outburst

4.2.2 Source of Ignition

Presence of combustible atmosphere in the mine can not cause a methane explosion by itself. An ignition source, even an arc or a spark, has to trigger the reaction. Representation of source of ignition was shown in Figure 4.1 previously. On the fault tree, possible sources of ignition considering underground coal mining operations and environment are divided into four categories, namely mechanical, electrical, spontaneous combustion, and open flame ignitions. Each of the four sources are connected by *OR* gate to the intermediate event.

Spontaneous combustion can occur in coalbeds with physical and chemical characteristics that permit the coal to oxidize at relatively low temperatures (Iannacchione *et al.*, 2008). It is the onset of burning when there is no external ignition source present, most frequently associated with the onset of smouldering combustion within bulk solids (Foster, 1992). The contact between a combustible material and oxygen results in an oxidation reaction and heat is released. While the reaction is so slow that it can be completely neglected at normal ambient temperatures, if the temperature is increased the rate of reaction increases exponentially. Foster (1992) indicated that for spontaneous combustion the solid must be porous and it must give rise to a rigid char when heated. The primary ingredient for the reaction is oxygen. The oxidation process can not occur if oxygen is not present. MSHA statistics reveal that spontaneous combustion accounted for 17% of the ignition sources of the 87 reported fires occured at underground coal mines between 1990 and 2000 (Iannacchione *et al.*, 2008). On the fault tree, by spontaneous combustion, also any other exothermic chemical reaction is referred. Within the scope of this study, these chemical ignition sources are not investigated. Therefore, it is left as an *undeveloped event*.

4.2.2.1 Mechanical Ignitions

The possible causes of mechanical ignitions were discussed in Chapter 2. In the light of this information, it is decided that the causes can be collected into three different categories as mechanical impact, friction, and misuse of the mechanical equipments. The three failure events are connected with *OR* gate to the intermediate event. Mechanical impacts are leaved as *undeveloped event* because it may be caused by any hit, strike or crash of equipments and the event has no further development within the scope of this research study.

Friction is an important factor considering mechanical ignitions. During the construction of fault tree, the three main potential friction sources in underground mining were taken into account separately; belt conveyors, coal winning machinery (longwall shearer's cutting), and rope haulage systems. Either one of the sources will result in dangerous sparks so they are connected with *OR* gate to the friction event. The first potential source of frictional ignition is cutting/grinding (coal winning machinery). Longwall shearer's cutting operation may be the direct cause of methane explosions, as in Upper Big Branch, 2010. Sufficient ventilation around the cutting drum is the primary prevention target against methane explosions. Ventilation practice was discussed in Section 4.2.1. Additional precautions related to ignition is divided into two as quenching the cutter pick with water and proper maintenance of cutting bits. The deficiencies related to cutting/grinding are connected with *OR* gate and stated on the fault tree as:

- Lack of/Improper water sprays (BE34) and
- LTA maintenance of bits (BE35).

Another friction source may be rope haulage systems. The pulleys and return wheels should be periodically serviced and lubricated. Rubbing of the ropes against solid surfaces such as, the roof, sides or floor of airways, and especially timber supports should also be avoided. Moreover, fluid couplings and enclosed gearings or direct drives has to be preferred to mechanical clutches or V-drives for the transmissions of mining machinery (McPherson, 2015). Lack of periodical maintaining the mechanical braking system is the last failure considering haulage systems. These four failure events are connected with *OR* gate to intermediate event rope haulage failures. The deficiencies related to rope haulage failures are listed as:

- LTA service/lubricating of pulleys (BE36),
- Rubbing against solid surfaces (BE37),
- Mechanical clutches (BE38), and
- LTA maintenance of mechanical braking (BE39).

The third and the last frictional sources of ignition are improper conveyor belts (Figure 4.6). Using conveyor belts that propagate fire is a crucial deficiency. Similarly, not having any temperature monitors or belt tension transducers that will isolate electrical power from the conveyor drive in abnormal conditions is another problem. Accumulation of dust or spillage around and especially underneath conveyors is the third failure on the fault tree considering belt conveyors. These three events will directly affect any spark coming from belt conveyors. The list of the failures related to conveyor belts are determined as:

- Belts propagating fire (BE40),
- Lack of temperature monitors (BE41), and
- Lack of dust suppression (BE42).

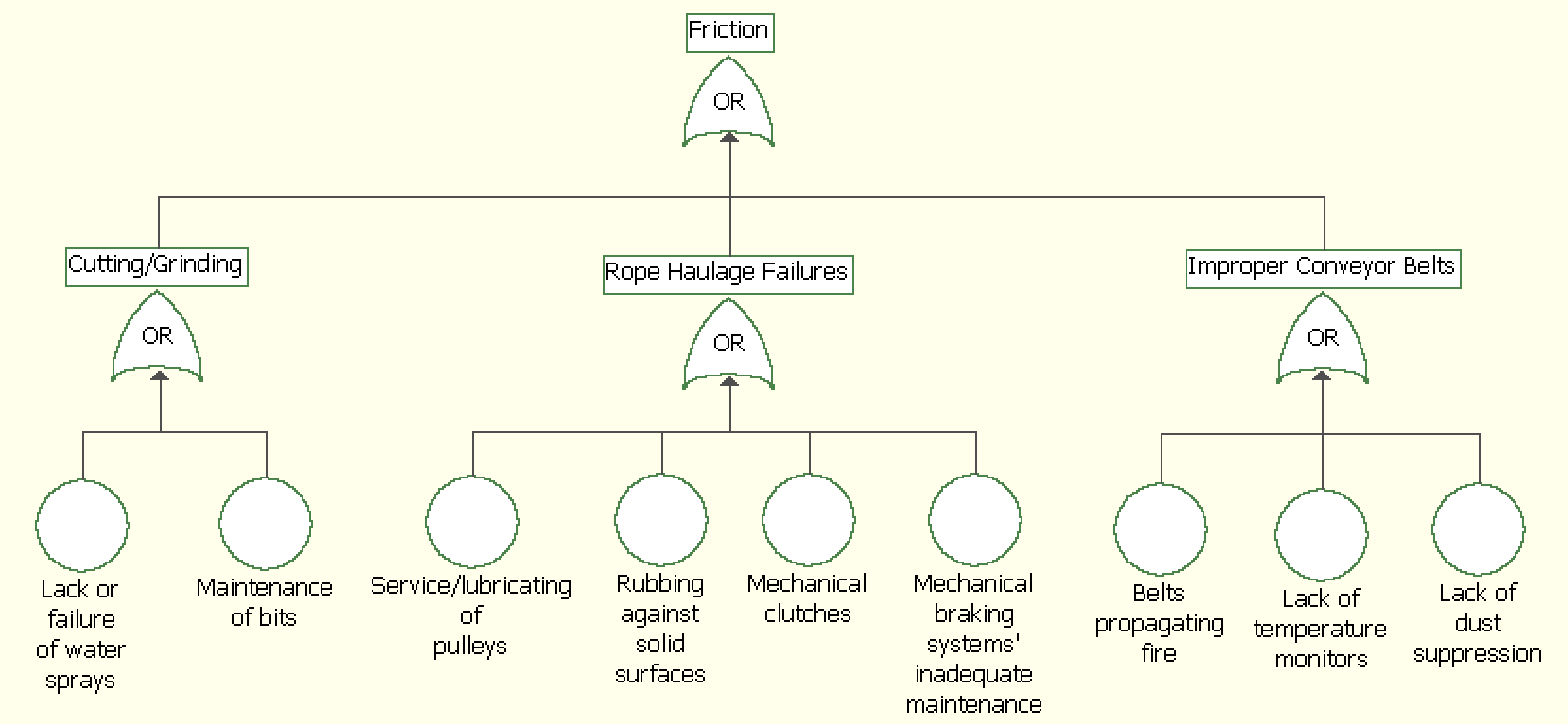


Figure 4.6 Fault tree of friction

The third intermediate event of mechanical ignitions is misuse of the mechanical equipment. Misuse of the equipment can occur in different ways (Figure 4.7). On the fault tree, the failure is divided into five categories. These are listed as:

- LTA maintenance of equipments (BE43),
- Lack of automatic cut-off (BE44),
- Running long periods (BE45),
- Bypassing/Removal of safety features (BE46), and
- Lack of on-board fire extinguishers (BE47).

LTA maintenance may cause various types of failures on the mechanical equipment and result in ignition. Lack of automatic cut-off with the help of pressure relief valves and thermal trips in abnormal conditions is another precaution against mechanical ignitions. Similarly, on-board fire extinguishers on especially vehicles and diesel equipment will help to prevent the expanding of a possible fire. Running the equipment for long periods cause hot surfaces on the equipments, which is an undesired situation in the mine. Bypassing/Removal of safety features on the equipment is generally related to human error. However, less than adequate auditing by the management and safety professionals of the workplace is also relevant.

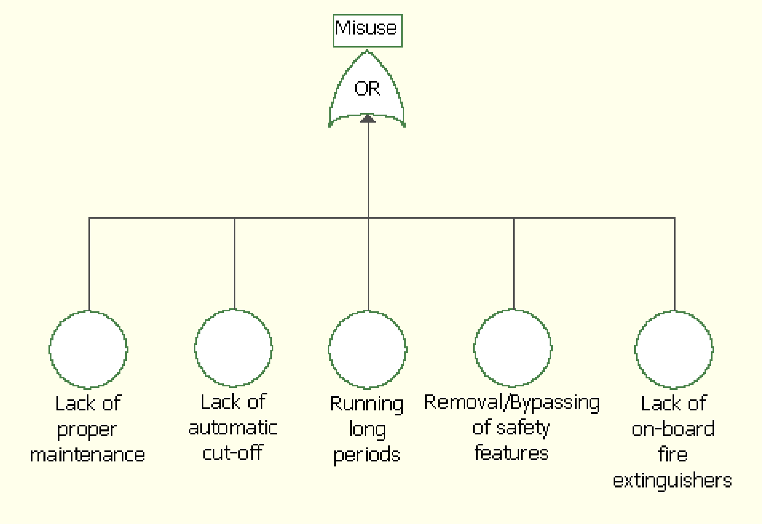


Figure 4.7 Fault tree of misuse

4.2.2.2 Electrical Ignitions

Another type of ignition in underground mining may result from electrical deficiencies. The major failure in this topic is not using intrinsically safe flameproof equipments, namely permissible equipments in the mine. Title 30 of the U. S. Code of Federal Regulations (CFR) contains federal coal mining safety regulations (30 CFR). The term permissible briefly refers to equipment that will not cause a mine explosion or mine fire considering its construction and maintenance procedures also. For example, 30 CFR 75.507 states that any atmospheric monitoring system operated during fan stoppages shall be intrinsically safe. The provision also comprises air quality detectors, measurement devices, telephones, and signaling devices in the following sections of the legislation. Besides, 30 CFR 75.500, 30 CFR 75.1002, and 30 CFR 75.507 emphasizes that the electrical equipment normally exposed to methane or coal dust closer to the working face than the last open crosscut, or within 150 feet of pillar workings or longwall faces, or in return entries, must be permissible (Dubaniewicz, 2009). Federal safety standards in the U.S.A. mandate that, “when 1% or more methane is present in a working place or an intake air course, electrically powered equipment in the affected area shall be de-energized, and other mechanized equipment shall be shut off”. The same concentration in Turkish legislation is 1.5%. The second failure event consists of bad electrical connections, short-circuit availability of electrical equipments, and improper cable locations and maintenance. These failures are not separated on the fault tree due to their relevance. Cables in airways should be hung in catenary method on cradles suspended from the roof. They should be located such that they will not be pinched by convergence or the yielding of roof supports, nor be impacted by vehicles. Other than the intermediate events electrostatical discharge and improper battery charging storages, the two basic events of electrical ignitions are:

- Nonpermissible equipments (BE48) and
- Bad electrical connection, cable laying (BE49).

Another electrical ignition source may be electrostatical discharge. The failure is divided into three; workers wearing rubber-soled footwear, inadeqautely grounded machinery, and not using anti-static materials for ducting, belts, and pipes (Figure 4.8). In addition to sparking caused by the misuse or damage to electrical equipment, electrostatic sparks may also be capable of igniting a flammable mixture of gases (McPherson, 2015). Electrostatic charges are built up on non-conducting (or poorly conducting) surfaces as a regular feature of many everyday operations and, particularly, at pointed or sharply curved regions on those surfaces. This may occur, for example, where belts run over pulleys, at the nozzles of compressed air jets and within non-conducting ventilation ducts. Even the charge that builds up on the human body in dry conditions can produce dangerous sparks (Strang and McKenzie-Wood, 1985). In such conditions, workers should not wear rubber-soled footwear. All machines with moving parts should be adequately grounded against the build-up of electrostatic charges (McPherson, 2015). Anti-static materials should be used for ducting, belts, and pipes. The three deficiencies related to electrostatical discharge are specified as:

- Inadeqaute grounding of machinery (BE50),
- Lack of antistatic ducting and belts (BE51), and
- Workers wearing rubber-soled footwear (BE52).

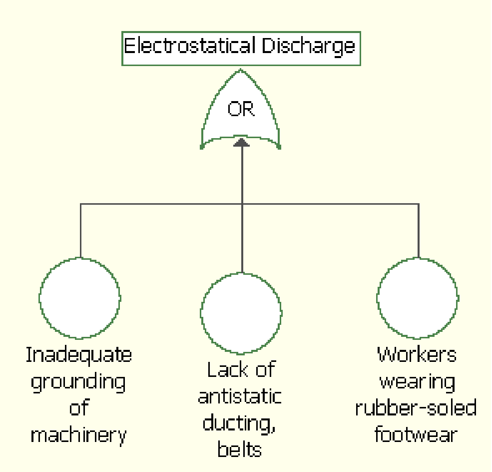


Figure 4.8 Fault tree of electrostatical discharge

Particular care should be given to dangerous locations in the mine such as, switchgear or battery charging stations and explosives or fuel storage magazines. They should not affected by convergence or falls of roof. Such areas should be located at properly supported places in the mine against potential roof falls or support failures. Lack of non-aqeous fire extinguishers in or near these areas is another problem (Figure 4.9). Precautions should be taken against electrical leakage in the vicinity of explosives or fuel storage areas. Therefore, basic events are listed as:

- Weak ground support around the storage (BE53) and
- Lack of non-aqeous fire extinguishers (BE54).

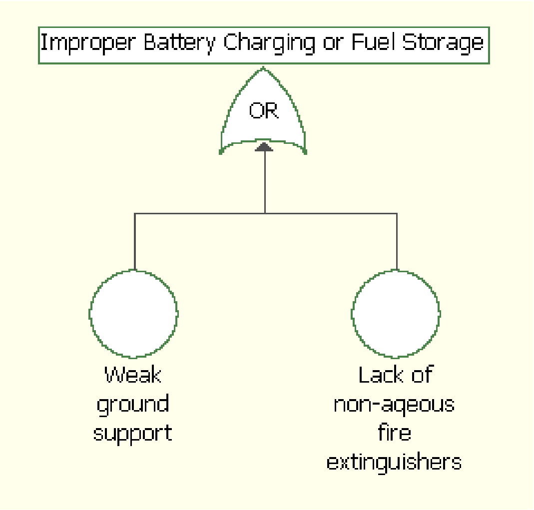


Figure 4.9 Fault tree of improper battery charging or fuel storage

4.2.2.3 Open Flame

The last source of ignition on the fault tree is determined as open flame ignitions. Two main types of open flame ignitions are specified as improper blasting operations and naked flame in the mine. Blasting operations in underground mining are specific practices which have to be performed with the utmost care. Many detailed deficiencies can be mentioned about blasting but in this study, six types of blasting failures are specified on the fault tree. All basic events are connected with *OR* gate to the intermediate event blasting operations and it is presented in Figure 4.10. The six deficiencies related to blasting operations are specified as:

- Using forbidden blasting components (BE55),
- Improper storage and handling of explosives (BE56),
- Using excess amount of explosives (BE57),
- Improper testing instruments (BE58),
- Improper blastholes (BE59), and
- Lack of gas measurement (BE60).

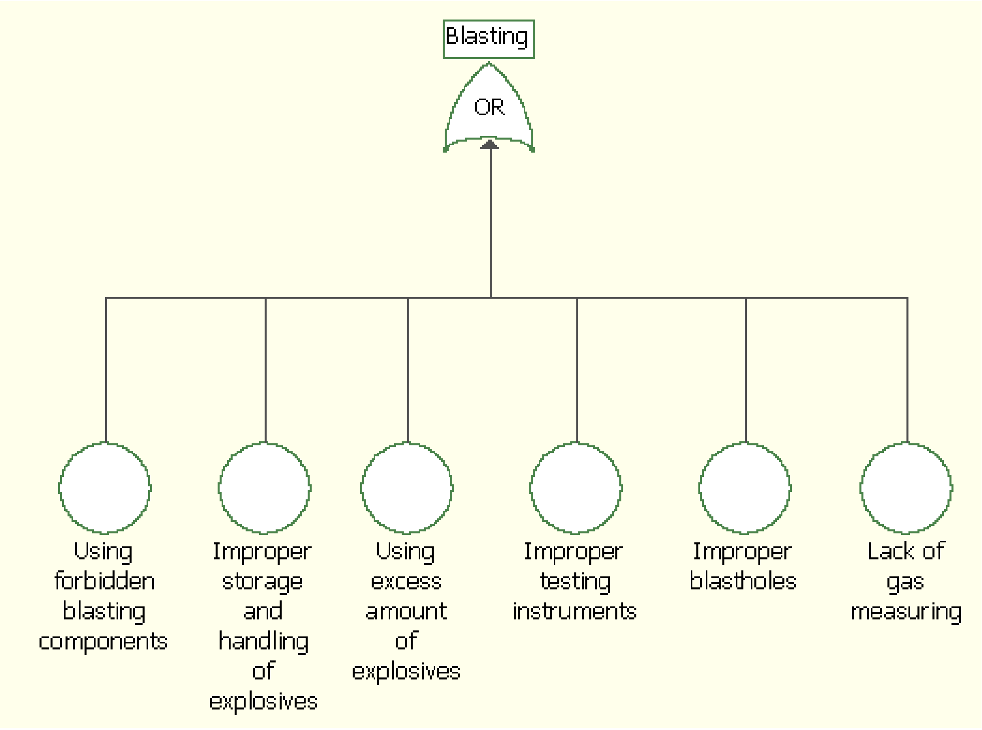


Figure 4.10 Fault tree of blasting

Naked flame ignitions are divided into two; cigarettes, matches, lighting and welding operations underground. If the workers think that the mine they work in has not got any methane presence or the ventilation of the mine is adequate, they may enter the mine with smoking materials. Insufficient training and insufficient auditing failures have to occur at the same time for that situation. Therefore, the two failures are connected with *AND* gate to the intermediate event (Figure 4.11). The two detected deficiencies related to this failure are listed as:

- Insufficient training (BE61) and
- Insufficient auditing (BE62).

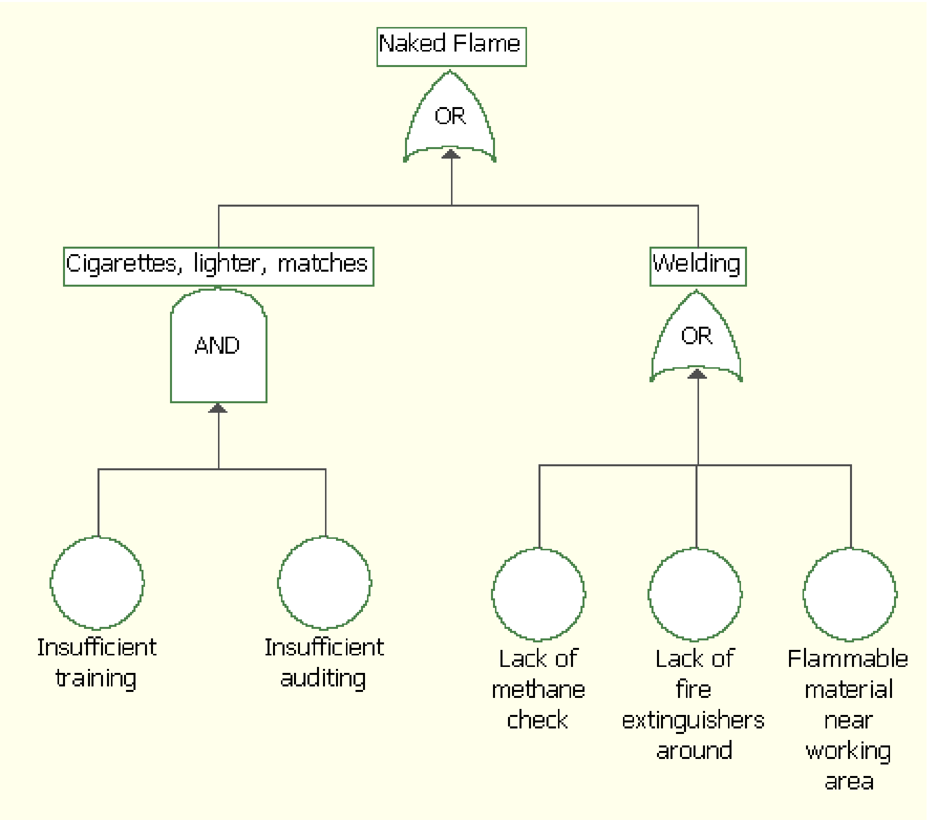


Figure 4.11 Fault tree of naked flame

Welding operations in underground coal mining are critical (similar to blasting) and should be associated with work permits in underground coal mining. Basic events of the welding operations are listed as:

- Lack of methane check (BE63),

- Flammable material near working area (BE64), and
- Lack of fire extinguishers around (BE65).

First of all, methane check is vital before and during welding operations. Hot slag and sparks from welding are easily capable of igniting combustible materials such as coal, wood, paper, and waste rags. Wherever possible, such materials should be removed from the vicinity of welding operations and the remainder wetted down or coated by stonedust. Fire extinguishers must be available at the sites of all welding operations in case of unwanted ignitions.

Following the formation of the fault tree, minimal cut sets were found. Cut sets are the smallest combination of failure events that result in the *top event*'s failure. Total of 35 cut sets are found considering the qualitative fault tree given in Figure 4.1. Oxygen supply is the common event in all of the sets due to being a *house event*. It is not mentioned in Table 4.1 in order to simplify the list. Block number and explanations of the cut sets are also given in Table 4.1. There are 24 cut sets consist of 3 blocks, 6 cut sets consist 3 blocks, 2 subsets, 4 cut sets consist of 3 blocks, 4 subsets, and 1 cut set consists of 3 blocks, 8 subsets. These sets were found by implementing BlockSim-7 software features to the tree. The software evaluates the failure probabilities of the cut sets by considering *AND* and *OR* gates of the qualitative fault tree.

Table 4.1 Minimal cut sets of the qualitative fault tree

Set Number	**Explanation**
1	Deficient primary ventilation, friction
2	Deficient primary ventilation, blasting
3	Failure in gas monitoring, friction
4	Deficient primary ventilation, misuse
5	Failure in gas monitoring, blasting
6	Deficient auxiliary ventilation, friction
7	Failure in gas monitoring, misuse
8	Deficient primary ventilation, naked flame
9	Deficient primary ventilation, electrostatical discharge

Table 4.1 Minimal cut sets of the qualitative fault tree (Continued)

Set Number	**Explanation**
10	Deficient auxiliary ventilation, blasting
11	Deficient primary ventilation, improper battery charging stations
12	Deficient auxiliary ventilation, misuse
13	Failure in gas monitoring, naked flame
14	Failure in gas monitoring, electrostatical discharge
15	Failure in gas monitoring, improper battery charging stations
16	Deficient auxiliary ventilation, naked flame
17	Deficient auxiliary ventilation, electrostatical discharge
18	Deficient primary ventilation, (one block from BE48, BE49)
19	Deficient auxiliary ventilation, improper battery charging stations
20	Roof falls, friction
21	Failure in gas monitoring, (one block from BE48, BE49)
22	Roof falls, blasting
23	Roof falls, misuse
24	Deficient auxiliary ventilation, (one block from BE48, BE49)
25	Roof falls, naked flame
26	Roof falls, electrostatical discharge
27	Roof falls, improper battery charging stations
28	Roof falls, (one block from BE48, BE49)
29	Methane outburst, friction
30	Methane outburst, blasting
31	Methane outburst, misuse
32	Methane outburst, naked flame
33	Methane outburst, electrostatical discharge
34	Methane outburst, improper battery charging stations
35	Methane outburst, (one block from BE48, BE49)

As Table 4.1 indicates, the most probable cut set is found as deficient primary ventilation and friction set. The second probable one is again deficient primary ventilation and blasting combination. These results are compared with the cut sets of quantitative FTA in Section 4.3.3. The least probable methane explosion cut set is found as methane outburst and nonpermissible equipment, or methane outburst and bad electrical connection, cable laying. All of the lower sets have methane outburst as the indicator of combustible atmosphere.

4.3 Quantitative Fault Tree Analysis

There were 3 major events, 27 intermediate events, and 65 basic events presented in qualitative FTA in Section 4.2 with their explanations. Quantitative fault tree is much more simpler than the qualitative one, because in order to determine the distribution types of basic events, time between failure data is needed and as mentioned before, data about methane explosions occured within TTK do not provide detailed resolutions of the events. Besides, methane explosions are one of the rarest type of accidents already, so the number of available time between failure inputs are limited.

The main objective for performing a quantitative FTA was to found the most significant failure event of a methane explosion, the mean time of the system, the particular time period in which the probability of failure (a methane explosion to occur) becomes 100%, and the cut sets of the quantitative fault tree. Also, observing the differences after excluding the most significant failure event from the fault tree is another substantial objective.

4.3.1 Formation of Fault Tree Analysis

Due to the limited size and availability of the accident data gathered from TTK, qualitative fault tree presented in Section 4.2 has to be simplified. An effective occupational accident data collection and interpretation in the future will help at increasing the number of basic events and providing a more detailed quantitative FTA. Fault tree presented in Figure 4.12 has two major events as combustible atmosphere and source of ignition with five basic events as deficient ventilation practice (X1), methane outburst (X2), mechanical ignitions (X3), electrical ignitions (X4), and blasting (X5). X1 and X2 are connected with *OR* gate to combustible atmosphere and X3, X4, and X5 are connected with *OR* gate to source of ignition.

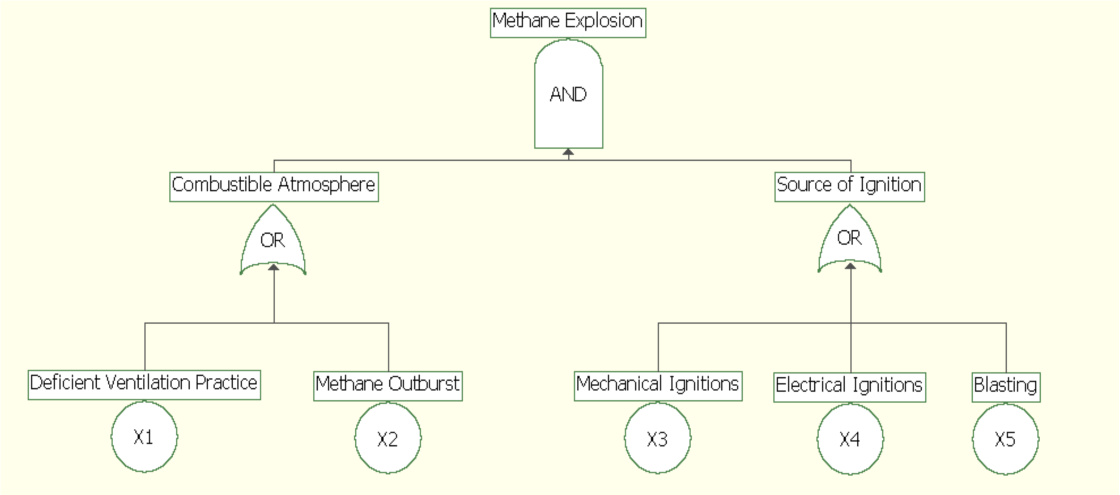


Figure 4.12 Quantitative fault tree of methane explosion

Combustible atmosphere and source of ignition are connected with *AND* gate to the *top event* methane explosion. The intermediate events presented on qualitative fault tree, primary ventilation practice, auxiliary ventilation practice, and failure in gas monitoring are combined under deficient ventilation practice. *Undeveloped event* roof falls is excluded. The two other *undeveloped events* mechanical impact and spontaneous combustion with *house events* oxygen supply and methane emission are also excluded for the quantitative fault tree. The *intermediate events* presented on the qualitative fault tree, misuse and friction are combined under mechanical ignitions, while electrostatical discharge, improper battery charging storages and the *basic events* nonpermissible equipments and bad electrical connection, cable laying, short-circuit are combined under electrical ignitions on the quantitative fault tree (Figure 4.12). The *intermediate event* naked flame is also excluded and only blasting is used as open flame ignitions. All of the above combinations and exclusions for quantitative FTA were made since there is not any recorded methane explosion caused by those combined or excluded failure events individually.

4.3.2 Probability Distributions of the Failure Events

Probability distributions of all five basic events are evaluated using ReliaSoft Weibull++7. In order to achieve that, failure (accident) dates of each event were presented to the software as input data. The distribution of each event using time between failure data was found in Weibull++7 environment. Therefore, the input data of the software is the months between two failures (accidents). Event distributions are found as Weibull 3-P distributions.

Weibull distribution is a specific distribution that is widely used in life data analysis. It is advantageous due to its versatility and relative simplicity. A distribution is mathematically defined by its *probability density function (pdf)* (Equation 3). The three parameter Weibull distribution has the general expression of (Weibull, 1951):

$$f(T) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \qquad \text{(Eq. 3)}$$

In Equation 3:

$f(T) \geq 0$, $T \geq 0$ or γ,

$\beta > 0$, $\eta > 0$,

$-\infty < \gamma < \infty$,

and: β is the shape parameter, also known as the Weibull slope

η is the scale parameter

γ is the location parameter

The results of distribution analysis of each event are given in Table 4.2.

Table 4.2 Distribution parameters of basic events

Event Distribution	Distribution Constants		
	β	**η**	**γ**
X1 (Weibull 3P)	0.7421	7.7484	0.7300
X2 (Weibull 3P)	0.9332	18.9330	0.2800
X3 (Weibull 3P)	0.6533	7.3934	0.9175
X4 (Weibull 3P)	0.6928	41.5328	13.1200
X5 (Weibull 3P)	1.1293	49.3955	-4.7050

Generally, the location parameter γ is not used, and the value for this parameter can be set to zero. When this is the case, the *pdf* equation reduces to that of the two-parameter Weibull distribution. An important aspect of the Weibull distribution is how the values of the shape parameter, β, and the scale parameter, η, affect such distribution characteristics as the shape of the *pdf* curve, the reliability and the failure rate. Weibull distributions with $\beta<1$ have a failure rate that decreases with time, also known as infantile or early-life failures. Weibull distributions with β close to or equal to 1 have a fairly constant failure rate, indicative of useful life or random failures. Weibull distributions with $\beta>1$ have a failure rate that increases with time, also known as wear-out failures (Reliability HotWire, 2002). These comprise the three sections of the classic "bathtub curve." A mixed Weibull distribution with one subpopulation with $\beta<1$, one subpopulation with $\beta=1$ and one subpopulation with $\beta>1$ would have a failure rate plot that was identical to the bathtub curve.

4.3.3 Fault Tree Analysis of the System

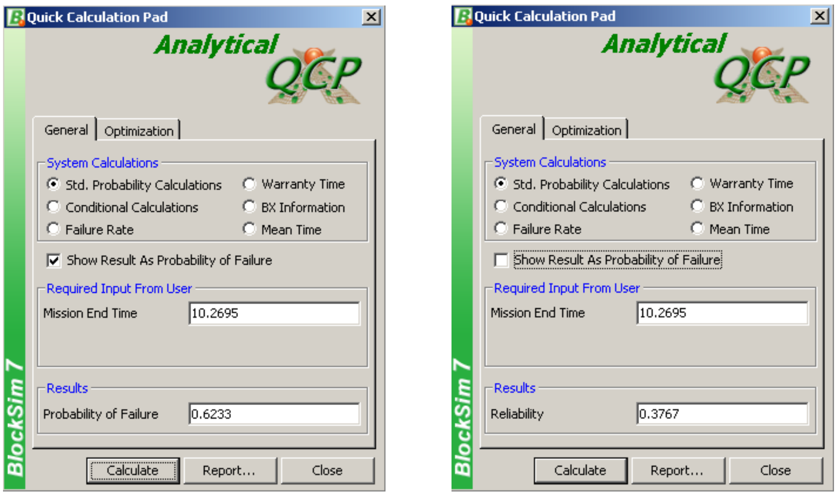
In this section, quantitative FTA of the system was conducted utilizing the tree presented in Section 4.3.1. To begin with, minimal cut sets of the system were found as in the qualitative FTA in Section 4.2. While there were 35 cut sets of the qualitative fault tree, 6 cut sets were obtained in the quantitative one, since it is a simpler version. One function of the cut sets is to simplify the tree and eliminate repetitive basic events. However, the quantitative fault tree of methane explosion is already a simple one. Therefore, the analysis resulted in six cut sets all of which include two events. The cut sets of the quantitative FTA are listed in Table 4.3 with their probability of failures for 50 months. These sets were found by utilizing BlockSim-7 software features. The software evaluates the failure probabilities of the cut sets by considering the distribution characteristics of basic events and also *AND* and *OR* gates of the quantitative fault tree.

Table 4.3 Minimal cut sets of the quantitative fault tree

Set Number	Name of the Set	Probability of Failure
1	Deficient ventilation, mechanical ignition	0.9493
2	Mechanical ignition, methane outburst	0.8855
3	Deficient ventilation, blasting	0.6614
4	Blasting, methane outburst	0.6169
5	Deficient ventilation, electrical ignition	0.5902
6	Electrical ignition, methane outburst	0.5506

It is seen from Table 4.3 that analyzing the given data, the highest probability of a methane explosion is deficient ventilation and mechanical ignition concurrence. It means the explosive methane presence would be a result of the deficient ventilation practice in the mine and the ignition would come from a mechanical source. The least probable concurrence for an explosion was found as electrical ignition and methane outburst. These results are similar with the qualitative FTA cut sets. The qualitative one has deficient primary ventilation with friction, which are simplified as deficient ventilation and mechanical ignition source in general during the construction of the quantitative one. Similarly, the least probable set is methane outburst and electrical ignition in quantitative FTA, while it is methane outburst and nonpermissible equipments or bad electrical connection, cable laying in the qualitative minimal cut sets.

Secondly, mean time of the system was found using Weibull++ 7 software. It is the time of an expected methane explosion occurence. The mean time of the system is found as 10.3 months, meaning there could be a methane explosion in the mine in average of approximately every 11 months. Considering this mean time, probability of failure and reliability of the system were also calculated. Probability of failure is the probability in a particular point of time that the system will fail, in other words a methane explosion will occur. As presented in Figure 4.13, according to the mean time (10.3 months) the system has a 62.33% of probability to fail.



● Std. Probability Calculations
○ Warranty Time
○ Conditional Calculations
○ BX Information
○ Failure Rate
○ Mean Time
☑ Show Result As Probability of Failure
Mission End Time 10.2695
Probability of Failure 0.6233

● Std. Probability Calculations
○ Warranty Time
○ Conditional Calculations
○ BX Information
○ Failure Rate
○ Mean Time
☐ Show Result As Probability of Failure
Mission End Time 10.2695
Reliability 0.3767

Figure 4.13 Probability of failure and reliability of the system in 10.3 months

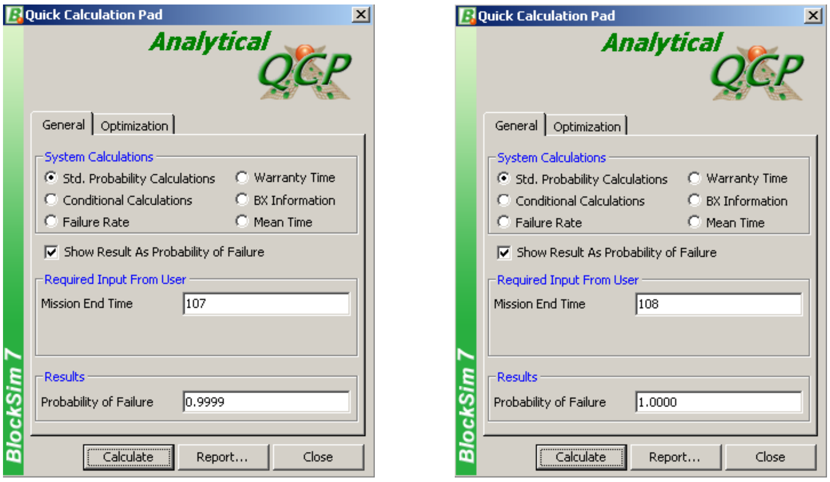
Probability of failure and reliability of the system at a given particular point in time are reciprocal, which means their summation is equal to one (Figure 4.13). Namely, probability of failure is also the unreliability of the system. Therefore, the reliability of the system in 10.3 months is found as 37.67%, which is also the probability of not to fail. The Weibull unreliability function, F(t), is also called cumulative distribution function (CDF) and represented by Equation 4 (Weibull, 1951):

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad \text{(Eq. 4)}$$

The reliability function of Weibull distribution is reciprocal of Equation 4 and shown by Equation 5 (Weibull, 1951):

$$R(t) = 1 - F(t) \qquad \text{(Eq. 5)}$$

Manually increasing the mission end time within the software will finally give the particular point in time when the system's probability of failure is 100%. Figure 4.14 shows the last part of this process. System's probability of failure was found as 108 months. It means a methane explosion is certain within 108 months (9 years), according to the given time between failure data and the quantitative fault tree.



System Calculations
● Std. Probability Calculations ○ Warranty Time
○ Conditional Calculations ○ BX Information
○ Failure Rate ○ Mean Time
☑ Show Result As Probability of Failure

Required Input From User
Mission End Time: 107

Results
Probability of Failure: 0.9999

System Calculations
● Std. Probability Calculations ○ Warranty Time
○ Conditional Calculations ○ BX Information
○ Failure Rate ○ Mean Time
☑ Show Result As Probability of Failure

Required Input From User
Mission End Time: 108

Results
Probability of Failure: 1.0000

Figure 4.14 Probability of failures for 107 and 108 months

The Probability Density Function (PDF) vs. Time plot of the system is given in Figure 4.15 for a period of 120 months. This plot gives the approximate probability value of the system at a given time.

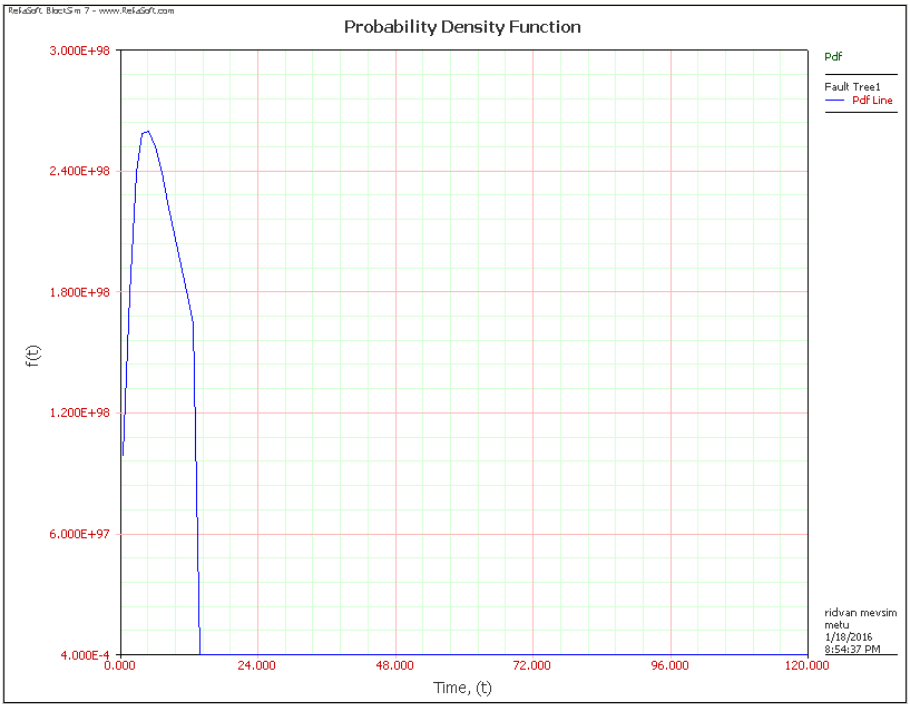


Figure 4.15 Probability Density Function vs. Time plot for 120 months

Failure rate (or hazard function) in Weibull distribution is given in Equation 6:

$$h(t) = \frac{\beta}{\eta}\ (\frac{t-\gamma}{\eta})^{\beta-1} \qquad \text{(Eq. 6)}$$

It can be seen that h(t)=F(t)/R(t). Unreliability vs. Time plot for each event is given in Figure 4.16 and Reliability importance vs. Time plot for each basic event in 120 months is given in Figure 4.17.

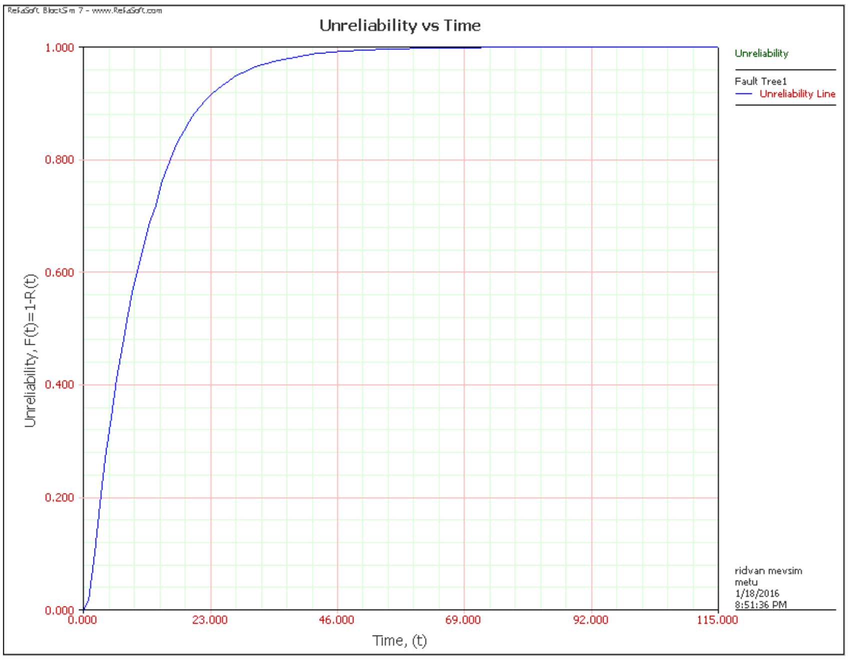


Figure 4.16 Unreliability vs. Time plot of the system for 115 months

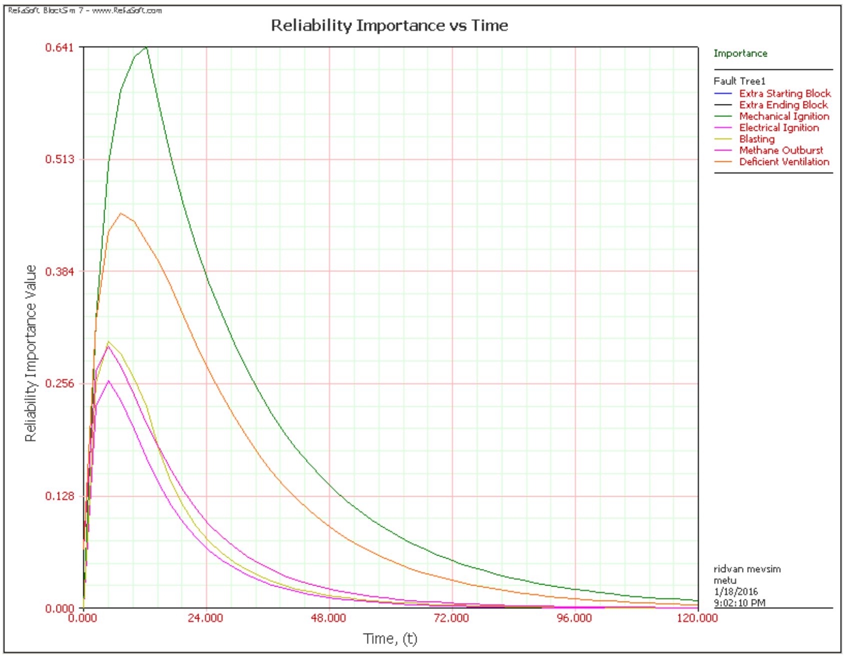


Figure 4.17 Reliability Importance vs. Time plot of basic events for 120 months

The event with the highest probability of failure for 120 months was found as mechanical ignitions. Reliability of importance and the static importance of basic events should be examined in order to determine the most important events in the system. Reliability of importance gives the relative importance of each event in a system with respect to the overall reliability of the system. By this way, the impact of each basic event can be evaluated. Preventing the events having the highest effects on the system will be more beneficial at the first step.

Static reliability importance vs. Time plot for 48 months (4 years) is given in Figure 4.18 The most significant event here is mechanical ignition. It is followed by deficient ventilation practice. The most reliable basic event is found as electrical ignition for 48 months. The color becoming red in Figure 4.18 refers to increasing probability of failure. Reliability of importance and static importance values of each failure event were calculated. The most significant failure event was found as mechanical ignition source. Deficient ventilation, methane outburst, blasting, and electrical ignition follow mechanical ignition, respectively. Importance of mechanical ignition is 0.140, while the importance of deficient ventilation has 0.093, methane outburst has 0.022, blasting has 0.014, and electrical ignition has 0.012 importance values.

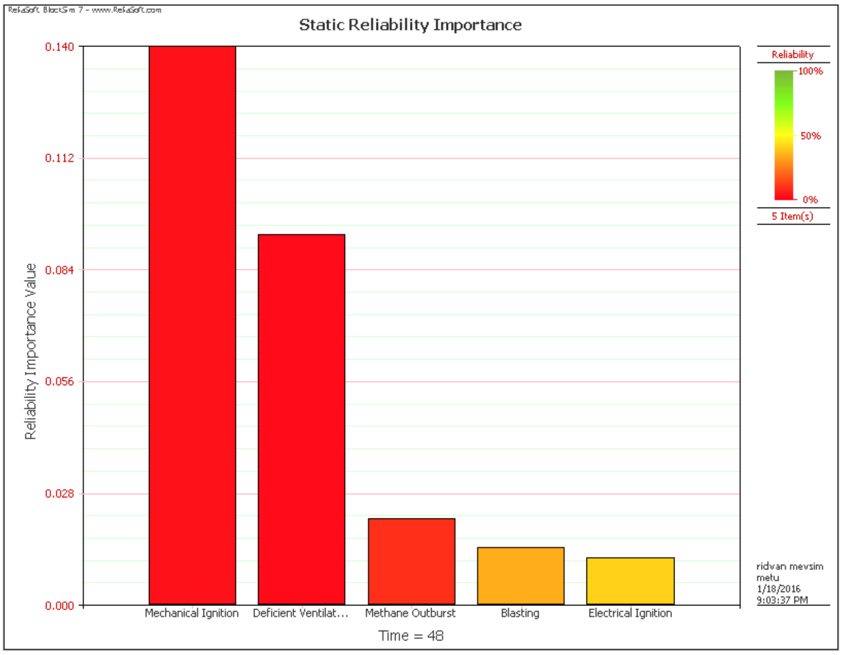


Figure 4.18 Static Reliability Importance vs. Time plot for each basic event

Excluding mechanical ignition, the most significant failure event for the system, from the system gives different results than before. The mean time of the system become 27.15 months with 64.69% probability to fail. The certain period of time in which a methane explosion has a 100% probability to occur was increased to 255 months (around 22 years) from 108 months (9 years). As it is seen, excluding the most important failure event from the fault tree affected the results in large scale. The same evaluation can be implemented also to other failure events.

4.4 Results and Discussion

Qualitative and quantitative FTA of methane explosions were conducted separately in this research study. During the construction of the qualitative fault tree, accident data obtained from TTK, three site investigations, and annual evaluation reports of Labor Inspection Board have assisted. The *top event* of the fault tree was specified as "Methane Explosion" considering underground coal mines. There were 3 major events (combustible atmosphere, oxygen supply, and source of ignition), 27 intermediate events, and 65 basic events constituted on the fault tree. Such a detailed fault tree of methane explosions is presented for the first time. The three major events generating an explosion were connected with *AND* gate to the top event. Total of 35 minimal cut sets were found for qualitative fault tree. The most probable set appeared as the deficient primary ventilation and friction combination. The second probable one was again deficient primary ventilation and blasting set. The least probable methane explosion cut set was found as methane outburst and nonpermissible equipment, or methane outburst and bad electrical connection, cable laying. All of the lower sets have methane outburst as the indicator of combustible atmosphere. These results were compared to the cut sets of quantitative FTA.

Secondly, the quantitative FTA was performed. Due to less than adequate investigation of previous methane explosions in detail, it was a simpler fault tree comparing to qualitative one. It has two major events as combustible atmosphere and source of ignition with five basic events as deficient ventilation practice (X1), methane outburst (X2), mechanical ignitions (X3), electrical ignitions (X4), and blasting (X5). X1 and X2 were connected with *OR* gate to combustible atmosphere and X3, X4, and X5 were again connected with *OR* gate to source of ignition. Quantitative fault tree has 6 minimal cut sets. Probability of failure values are similar to the qualitative tree. Again, deficient ventilation and mechanical ignition source appears as the most expected combination to cause a methane explosion. The least probable set was found as methane outburst and electrical ignition source joining.

Within the quantitative FTA, distributions of the five basic events were obtained as Weibull 3P via Weibull++ 7 software. The mean time of the system was found as 10.3 months, meaning there could be a methane explosion in the mine in an average of approximately every 11 months. Considering this mean time, probability of failure and reliability of the system were also calculated. According to the mean time (10.3 months) the system has a 62.33% of probability to fail. Manually increasing the mission end time within the software finally gave the particular point in time when the system’s probability of failure was found as 100%. System’s probability of failure was found as 108 months. It means a methane explosion is certain within 108 months (9 years), according to the given time between failure data and the quantitative fault tree.

One of the most important findings of the study was the prioritizing of five basic events considering their impacts on a possible methane explosion. All the evaluations were made via BlockSim-7 software. Mechanical ignition source was found as the most affecting failure event of a methane explosion, considering the obtained accident data from TTK. Deficient ventilation, methane outburst, blasting, and electrical ignition follow mechanical ignition, respectively. Importance of mechanical ignition is 0.140, while the importance of electrical ignition is 0.012. Excluding mechanical ignition from the system gives different results. The mean time of the system become 27.1 months with 64.69% probability to fail. The certain period of time in which a methane explosion has a 100% probability to occur was increased to 255 months from 108 months. As it is seen, excluding the most important failure event from the fault tree affected the results in large scale. The same evaluation can be implemented also to other failure events.

Quantitative FTA studies of methane explosions are limited in OSH literature, as mentioned before, and there is not available previous inferences to directly compare with the quantitative results of this study. However, qualitative FTA studies are present and it was observed that at least the first two steps of the main fault tree is similar with the previous studies. Presence of the combustible atmosphere mainly depends on the efficieny of mine ventilation, while the ignition sources are generally divided into mechanical and electrical ignitions with also blasting operations. However, the qualitative fault tree presented in this study goes further and contains detailed resolutions of the failure events.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main conclusions drawn from this study is listed as:

- Focusing on TTK, total of 67 methane explosions resulted in 815 fatalities (22% of all fatalities) between 1875-2014. Kozlu has the biggest share among five enterprises with 56% (455 fatalities) of overall and appears as the most fatal enterprise. Karadon follows Kozlu with 159 fatalities and 20% share.

- There were 65 basic events constituted on the qualitative fault tree of methane explosion. The three major events are determined as the presence of combustible atmosphere, oxygen supply (as the house event), and source of ignition.

- Total of 35 minimal cut sets were found in qualitative FTA, while 6 cut sets were found in the quantitative one. Both of them have similar results as deficient ventilation and mechanical ignition (due to friction, misuse, or mechanical impact) appearing as the most expected combination to cause a methane explosion. Also, the least probable set was found as methane outburst and electrical ignition source joining considering both qualitative and quantitative FTA.

- Mean time of the system was found as approximately 11 months with the probability of failure of 62.33%. The particular period of time in which a methane explosion has a 100% of probability to occur was found as 108 months (9 years).

- Reliability of importance and static importance values of each failure event were calculated. The most significant failure event was found as mechanical ignition source. Deficient ventilation, methane outburst, blasting, and electrical ignition follow mechanical ignition, respectively. Importance of mechanical ignition is 0.140, while the importance of deficient ventilation has 0.093, methane outburst has 0.022, blasting has 0.014, and electrical ignition has 0.012 importance values.

- Excluding mechanical ignition from the system gives different results. The mean time of the system become 27.1 months with 64.69% probability to fail. The certain period of time in which a methane explosion has a 100% probability to occur was increased to 255 months (around 22 years) from 108 months (9 years).

5.2 Recommendations

Main recommendations for future studies in this research area are listed as the following:

- The risks of mining were studied in Turkey previously, but until the 21st century, a professional risk analysis was an unfamiliar document to see at workplaces. Today, most of the mining companies, both private ones and public institutions, use 5 x 5 matrix technique. Although this is one of the simplest techniques, which does not require any advanced mathematical or statistical knowledge, there are still some major mistakes in its implementation in the field. For example, while evaluating the risk of methane explosion, the likelihood will be 1 (a rare situation) and the severity will be 5 (catastrophic results). Therefore, multiplication (1 x 5) will give the result of 5, which is located at the “green area” (safe area). However, the risk of a methane explosion can not be evaluated as an acceptable risk. It is a basic but frequently seen mistake of risk analysis perception and implementation. Besides, even a company is eager to prepare and apply a risk analysis, it can not reach the accident history and relevant data of its workplace, which is a primary requirement in the process.

- Companies should implement complex safety systems, adapt risk management techniques, advance in mine research, technology, and equipment, and legislation. For example, methane drainage should be researched in detail and its feasibility should be carried out thoughtfully.

- Lack of/unreliable occupational accident data is a major problem for risk assessment studies. Besides, just recording the accident is not enough. Analyzing the root causes, discussing possible deficiencies led to the accident, and remarking the proper prevention strategies are some of the required studies even after a small-scaled accident. Occupational accident and occupational disease notification system is still not satisfying in Turkey. Automated data transfer should be used and the coordination between companies and public administrations should be supplied.

- This research study revealed again that not only mining engineers but also mechanical and electrical engineers and technicians are vital for an underground mine. Mechanical ignitions appear as the most significant failure event considering methane explosions. Misuse and frictional ignitions can be prevented by internal auditing and proper maintenance and utilization of the equipments. Besides, lack of/Improper permissible equipments, improper stationary and hand held gas measuring devices, lack of/improper early warning systems, inadequate assessment of methane explosion risk, ventilation in series circuit, and lack of/improper spare ventilation fans and generation units are commonly seen deficiencies in Turkish mining industry. They have to be studied in particular care in order to prevent methane explosions.

- It is important that all personnel involved in the design and operation of the mine should have some knowledge about the prevention and detection of subsurface fires and explosions, procedures of personnel warning systems, escapeways, firefighting, toxic gases, training, fire drills and the vital need for prompt response to an emergency situation. The manner in which a major explosion in a mine is handled depends largely on the forethought and planning that has been expanded on such an eventuality.

- The certain protection against the initiation and hazards of methane explosions is training and practice of safety procedures. Classes and practical sessions should be held, not only for new recruits, but at regular intervals of time for all employees. These sessions should include discussions on the causes of explosions and how they propagate. Ventilation and safety engineers should engage in various scenarios and computer simulations of emergency situations.

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APPENDIX

FATAL OCCUPATIONAL ACCIDENTS in TTK BETWEEN 1875-2014

Table A.1 Methane explosions resulted in fatalities in TTK between 1875-2014 (TTK, 2015)

Methane Explosions		
Date of the Accident	**Location**	**Fatalities**
18.01.1927	Kozlu	1
25.01.1927	Kozlu	1
27.02.1939	Kozlu	24
01.01.1941	Üzülmez	1
20.01.1942	Üzülmez	2
03.12.1942	Armutçuk	63
26.03.1947	Kozlu	1
01.06.1947	Kozlu	5
21.09.1947	Kozlu	48
04.10.1947	Karadon	1
17.07.1948	Kozlu	1
05.11.1948	Armutçuk	4
09.08.1949	Üzülmez	1
05.09.1952	Karadon	1
22.03.1953	Kozlu	1
04.09.1953	Üzülmez	1
10.06.1954	Üzülmez	6
20.08.1954	Kozlu	13
23.01.1955	Karadon	54
08.06.1955	Armutçuk	2
24.04.1956	Armutçuk	8
24.02.1957	Kozlu	1
19.03.1957	Kozlu	1
23.03.1957	Kozlu	1

Table A.1 Methane explosions resulted in fatalities in TTK between 1875-2014 (TTK, 2015) (Continued)

Methane Explosions		
Date of the Accident	**Location**	**Fatalities**
14.12.1960	Kozlu	25
31.10.1961	Kozlu	1
15.02.1962	Karadon	4
30.12.1963	Karadon	1
19.02.1965	Kozlu	1
01.12.1965	Armutçuk	10
10.05.1966	Üzülmez	1
01.06.1967	Karadon	1
20.10.1967	Karadon	1
30.12.1968	Kozlu	5
11.09.1969	Karadon	16
22.03.1970	Üzülmez	2
30.06.1970	Kozlu	4
27.08.1970	Armutçuk	7
02.09.1970	Üzülmez	1
03.01.1971	Armutçuk	1
21.07.1971	Karadon	1
12.11.1971	Armutçuk	1
21.08.1972	Karadon	1
16.09.1972	Armutçuk	3
23.10.1972	Kozlu	24
09.08.1973	Kozlu	2
14.04.1974	Karadon	2
01.08.1974	Amasra	1
28.10.1975	Karadon	13
01.05.1976	Karadon	1
03.08.1977	Üzülmez	4
24.04.1978	Armutçuk	17
12.08.1979	Karadon	6
07.03.1983	Armutçuk	103
11.04.1983	Kozlu	11
31.01.1990	Amasra	5
03.03.1992	Kozlu	263
02.03.2004	Karadon	4
17.05.2010	Karadon	30

Table A.2 Asphyxiation/Suffocation accidents resulted in fatalities in TTK between 1875-2014 (TTK, 2015)

Asphyxiation/Suffocation Accidents		
Date of the Accident	**Location**	**Fatalities**
10.02.1939	Kozlu	1
08.05.1939	Kozlu	1
05.10.1939	Kozlu	1
21.10.1939	Kozlu	3
04.09.1953	Üzülmez	2
04.12.1953	Üzülmez	1
18.09.1954	Üzülmez	1
19.10.1954	N/A*	1
21.09.1955	Armutçuk	1
07.02.1956	Armutçuk	1
13.09.1956	Üzülmez	1
19.02.1965	Kozlu	1
16.12.1965	Karadon	1
10.05.1966	Üzülmez	1
01.06.1967	Karadon	1
29.01.1969	Karadon	1
19.08.1969	Karadon	1
16.11.1969	Karadon	1
13.01.1970	Karadon	4
12.02.1970	Kozlu	2
22.03.1970	Üzülmez	2
05.04.1971	Üzülmez	1
21.07.1971	Karadon	1
28.09.1971	Kozlu	1
14.06.1972	Üzülmez	2
21.08.1972	Karadon	1
15.08.1973	Armutçuk	1
15.09.1974	Kozlu	3
23.10.1974	Kozlu	1
23.08.1975	Armutçuk	1
01.05.1976	Karadon	1
13.08.1976	Armutçuk	7
31.08.1976	Üzülmez	1
17.04.1977	Karadon	1
09.06.1977	Armutçuk	1
05.07.1977	Kozlu	1
19.01.1978	Amasra	1
07.03.1978	Kozlu	1
23.04.1978	Kozlu	1
16.05.1978	Karadon	1

Table A.2 Asphyxiation/Suffocation accidents resulted in fatalities in TTK between 1875-2014 (TTK, 2015) (Continued)

Asphyxiation/Suffocation Accidents		
Date of the Accident	**Location**	**Fatalities**
28.07.1978	Armutçuk	2
28.06.1979	Karadon	1
12.08.1979	Karadon	6
09.05.1980	Kozlu	2
21.05.1980	Kozlu	1
24.09.1980	Kozlu	1
16.12.1980	Karadon	1
25.10.1982	Armutçuk	1
04.07.1983	Kozlu	1
30.08.1983	Armutçuk	3
27.09.1985	Üzülmez	1
01.07.1988	Karadon	2
28.08.1989	Amasra	2
08.10.1990	Karadon	1
31.01.1992	Kozlu	1
15.06.1992	Amasra	1
22.12.1993	Karadon	4
10.10.1994	Amasra	1
26.05.1995	Üzülmez	1
08.08.1995	Üzülmez	1
23.09.2000	Karadon	1
19.12.2002	Karadon	2
14.10.2003	Kozlu	1
02.03.2004	Karadon	1
18.05.2005	Kozlu	3
16.06.2005	Karadon	5
01.01.2006	Amasra	N/A
17.11.2006	N/A	N/A
09.03.2007	N/A	N/A
25.06.2007	Karadon	1
12.11.2007	Karadon	N/A
01.01.2008	Karadon	N/A
10.02.2009	Karadon	2
04.09.2010	Karadon	1
07.09.2010	N/A	N/A
05.01.2013	N/A	N/A
15.01.2013	N/A	N/A
13.03.2013	N/A	N/A

* N/A: Not available.

Table A.3 Methane outbursts resulted in fatalities in TTK between 1875-2014 (TTK, 2015)

Methane Outburst		
Date of the Accident	**Location**	**Fatalities**
23.05.1972	Karadon	2
19.06.1972	Armutçuk	3
20.11.1972	Karadon	1
14.04.1974	Karadon	2
06.03.1975	Karadon	3
19.11.1975	Kozlu	2
19.06.1976	Kozlu	1
03.03.1978	Kozlu	2
28.05.1979	Kozlu	1
19.11.1980	Karadon	1
30.05.1983	Kozlu	1
17.07.1984	Karadon	1
27.10.1984	Karadon	1
04.04.1991	Kozlu	1
14.02.2000	Karadon	1
19.12.2002	Karadon	2
22.03.2003	N/A*	N/A
14.10.2003	Kozlu	1
02.03.2004	Karadon	1
30.12.2004	Karadon	4
16.06.2005	Karadon	5
10.02.2009	Karadon	2
31.03.2011	Karadon	N/A
15.04.2011	Karadon	N/A
07.01.2013	Kozlu	8

* N/A: Not available.

Table A.4 Blasting accidents resulted in fatalities in TTK between 1875-2014 (TTK, 2015)

Blasting Accidents		
Date of the Accident	**Location**	**Fatalities**
26.04.1938	N/A*	1
08.05.1938	N/A	1
12.09.1938	N/A	1
14.12.1938	N/A	1
15.01.1942	Üzülmez	1
10.02.1944	Üzülmez	1
08.05.1953	Armutçuk	1

Table A.4 Blasting accidents resulted in fatalities in TTK between 1875-2014 (TTK, 2015) (Continued)

Blasting Accidents		
Date of the Accident	**Location**	**Fatalities**
30.06.1954	Karadon	1
12.06.1958	Karadon	4
16.01.1965	Kozlu	1
20.01.1965	Karadon	1
10.12.1973	Karadon	1
27.06.1979	Üzülmez	1
18.04.1981	Karadon	1
14.04.1995	Amasra	1
27.02.1999	Amasra	1
19.07.2000	Üzülmez	1
19.03.2005	Armutçuk	1

* N/A: Not available.

Table A.5 Electrical accidents resulted in fatalities in TTK between 1875-2014 (TTK, 2015)

Electrical Accidents		
Date of the Accident	**Location**	**Fatalities**
10.04.1954	Armutçuk	1
08.02.1957	Karadon	1
29.07.1958	Karadon	1
01.12.1960	Karadon	1
08.02.1962	Karadon	1
24.08.1966	Karadon	1
22.06.1972	Karadon	2
22.12.1973	N/A*	1
05.06.1985	Amasra	1
21.09.1990	Üzülmez	1
16.06.2000	Üzülmez	1

* N/A: Not available.

Table A.6 Mechanical accidents resulted in fatalities in TTK between 1875-2014 (TTK, 2015)

Mechanical Accidents		
Date of the Accident	**Location**	**Fatalities**
30.05.1941	Karadon	N/A*
25.05.1975	Kozlu	N/A
21.08.1975	Üzülmez	N/A
09.01.1976	Armutçuk	N/A
27.04.1976	Karadon	N/A
15.06.1976	Kozlu	N/A
22.08.1976	N/A	N/A
10.09.1977	Üzülmez	N/A
20.01.1978	Armutçuk	N/A
07.02.1978	Amasra	N/A
12.04.1978	Kozlu	N/A
28.11.1978	Üzülmez	N/A
06.06.1979	Amasra	N/A
23.10.1981	Karadon	N/A
17.09.1987	Karadon	N/A

* N/A: Not available.