Risk Assessment of Transformer Fire Protection in a Typical New Zealand High-Rise Building

By

Anthony Kwok-Lung Ng

Supervised by

Dr Michael Spearpoint

A research thesis presented as partial fulfilment of the requirements for the degree of
Master of Engineering in Fire Engineering

Department of Civil Engineering
University of Canterbury
Christchurch, New Zealand

ABSTRACT

Prescriptively, the requirement of fire safety protection systems for distribution substations is not provided in the compliance document for fire safety to the New Zealand Building Code. Therefore, the New Zealand Fire Service (NZFS) has proposed a list of fire safety protection requirements for distribution substations in a letter, dated 10th July 2002. A review by Nyman [1], has considered the fire safety requirements proposed by the NZFS and discussed the issues with a number of fire engineers over the last three years. Nyman concerned that one of the requirements regarding the four hour fire separation between the distribution substation and the interior spaces of the building may not be necessary when considering the risk exposure to the building occupants in different situations, such as the involvement of the sprinkler systems and the use of transformers with a lower fire hazard.

Fire resistance rating (FRR) typically means the time duration for which passive fire protection system, such as fire barriers, fire walls and other fire rated building elements, can maintain its integrity, insulation and stability in a standard fire endurance test. Based on the literature review and discussions with industry experts, it is found that failure of the passive fire protection system in a real fire exposure could potentially occur earlier than the time indicated by the fire resistance rating derived from the standard test depending on the characteristics of the actual fire (heat release rate, fire load density and fire location) and the characteristics of the fire compartment (its geometric, ventilation conditions, opening definition, building services and equipment). Hence, it is known that a higher level of fire safety, such as 4 hour fire rated construction and use of sprinkler system, may significantly improve the fire risk to health of safety of occupants in the building; however, they could never eliminate the risk.

This report presents a fire engineering Quantitative Risk Assessment (QRA) on a transformer fire initiating in a distribution substation inside a high-rise residential and commercial mixed-use building. It compares the fire safety protection requirements for distribution substations from the NZFS to other relevant documents worldwide: the regulatory standards in New

Zealand, Australia and United States of America, as well as the non-regulatory guidelines from other stakeholders, such as electrical engineering organisation, insurance companies and electricity providers. This report also examines the characteristics of historical data for transformer fires in distribution substations both in New Zealand and United States of America buildings. Reliability of active fire safety protection systems, such as smoke detection systems and sprinkler systems is reviewed in this research.

Based on the data analysis results, a fire risk estimate is determined using an Event Tree Analysis (ETA) for a total of 14 scenarios with different fire safety designs and transformer types for a distribution substation in a high-rise residential and commercial mixed-use building. In Scenario 1 to 10 scenarios, different combinations of fire safety systems are evaluated with the same type of transformer, Flammable liquid (mineral oil) insulated transformer. In Scenario 11 to Scenario 14, two particular fire safety designs are selected as a baseline for the analysis of transformer types. Two types of transformer with a low fire hazard are used to replace the flammable liquid (mineral oil) insulated transformer in a distribution substation. These are less flammable liquid (silicone oil) insulated transformers and dry type (dry air) transformers. The entire fire risk estimate is determined using the software package @Risk4.5.

The results from the event tree analysis are used in the cost-benefit analysis. The cost-benefit ratios are measured based on the reduced fire risk exposures to the building occupants, with respect to the investment costs of the alternative cases, from its respective base case.

The outcomes of the assessment show that the proposed four hour fire separation between the distribution substations and the interior spaces of the building, when no sprinkler systems are provided, is not considered to be the most cost-effective alternative to the life safety of occupants, where the cost-benefit ratio of this scenario is ranked fifth. The most cost-effective alternative is found to be the scenario with 30 minute fire separation and sprinkler system installed. In addition to the findings, replacing a flammable liquid insulated transformer with a less flammable liquid insulated transformer or a dry type transformer is generally considered to be economical alternatives.

From the QRA analysis, it is concluded that 3 hour fire separation is considered to be appropriate for distribution substations, containing a flammable liquid insulated transformer and associated equipment, in non-sprinklered buildings. The fire ratings of the separation construction can be reduced to 30 minute FRR if sprinkler system is installed. This conclusion is also in agreement with the requirements of the National Fire Protection Association (NFPA).

ACKNOWLEDGEMENTS

I would like to take the chance to express my gratitude to all who have put their effort and support in helping me to complete this research.

- Thank you to my supervisor, Michael Spearpoint, for his guidance throughout the research. I am grateful to him for answering all my queries promptly and with patience.

- Thanks to Ove Arup Pty Ltd for the ArupFire Scholarship in 2005.

- Thank you to all my lecturers especially Charley Fleischmann, Michael Spearpoint, Erica Seville, Andy Buchanan and David Purser, who have all helped in the fire courses and make them both interesting and challenging.

- My appreciation to the following persons who provided much technical advice and significant information to this study:

    - Jonathan Nyman for his initiative and advice on the project;
    - Wade Enright for his excellent description of the entire transformer system and good suggestions;
    - John Fraser, Vince Duffin, Tim O'Brien, Andre Mierzwa, Shane Watson, Trevor Buckley, Colin Sydenham and Johannes Dimyadi, for their involvement and effort in the discussion of transformer fire hazards in distribution substations and the fire protection systems;
    - Pat Hurley for his support in providing the retail prices and the specifications of transformers and associated equipment;
    - Ian Munor for sharing his invaluable experience and knowledge on the ability of firefighters to control transformer fires.

- Thank you to the New Zealand Fire Service (April Christensen, Neil Challands, and Alan Merry) and the National Fire Protection Association (Nacy Schwartz) for providing me with the invaluable statistical and historical data from their database. Without this data, I believe the outcome of the research would be invalid and non-representative.

- Thanks to my friends and all fire-mates in 2005 and 2006, for their friendship, help and laughter. Special thanks to Daniel Ho and Karen Chen for their support and encouragement.

- Thanks to Delwyn Lloydd, Nathaniel Petterson, and Vincent Ho for their excellent proof-reading skill.

- Last but not least, I wish to thank my family for their love and support throughout. Special thanks to Uncle Frankie Lam for his financial support.

NOMENCLATURE

Abbreviations

NZBC	New Zealand Building Code
NZFS	New Zealand Fire Service
FIRS	Fire Incident Reporting System
NFPA	National Fire Protection Association
BCA	Building Code of Australia
IEEE	Institute of Electrical and Electronics Engineers
EMV	Equivalent Monetary Value
QRA	Quantitative Risk Analysis
HV/ LV	High Voltage/ Low Voltage
AC	Alternative current
e.m.f	Electromagnetic field
PCB	Polychlorinated biphenyl
FHC	Fire Hazard Category
FRR	Fire Resistance Rating
ETA	Event Tree Analysis
FTA	Fault Tree Analysis

Definitions

Flash point	Minimum temperature of a liquid at which it produces a flammable vapour
Fire point	The lowest temperature of a liquid at which it produces a sufficient vapour that can sustain a continuous flame
Risk estimate	Process used to assign values to the probability and consequences of a risk as defined by the international standard organisation ISO [2]
Purpose group	The classification of spaces within a building according to the activity for which the spaces are used as defined by the compliance document C/AS1 [3].
Fire hazard category	The number (grade 1 to grade 4 in order of increasing severity) used to classify purpose groups or activities having a similar fire hazard, and where fully development fires are likely to have similar impact on the structural stability of the building as defined by the compliance document C/AS1 [3].
Firecell	Any space including a group of contiguous spaces on the same or different levels within a building, which is enclosed by any combination of fire separations, external walls, roofs, and floors as defined by the compliance document C/AS1 [3].
Escape height	The height between the floor level in the firecell being considered and the floor level of the required final exit which is the greatest vertical distance above or below that firecell as defined by the compliance document C/AS1 [3].
Distribution substation	The substation that converts the voltage to a level adapted for household use (i.e. 415V in 3 phases or 240V in one phase), which contains transformers, power cables, electrical components and protection devices. In this research, distribution substation is defined as a substation containing a 750kVA transformer and the associated electrical equipment in a single room inside a residential and commercial mixed-use building. Noted that other articles may use the name of “transformer rooms” or “transformer vaults”. These are considered to be equivalent to distribution substations.

List of Contents

ABSTRACT i
ACKNOWLEDGEMENTS iv
NOMENCLATURE vi
  Abbreviations vi
  Definitions vii
LIST OF FIGURES xi
LIST OF TABLES xiii
CHAPTER 1 INTRODUCTION 1
  1.1 Impetus for Research 1
  1.2 Objective of this Research 4
  1.3 Scope of this Research 5
  1.4 Report Outline 6
CHAPTER 2 BACKGROUND 7
  2.1 Electrical Distribution 7
    2.1.1 Power Generation 7
    2.1.2 Electric Power Transmission 7
  2.2 Distribution Substation 9
  2.3 Overview of Transformers 10
    2.3.1 General Construction of Transformers 10
    2.3.2 Transformer Fundamental Theory 12
    2.3.3 Transformer Type 14
    2.3.4 Potential Transformer Problems and Protections 16
CHAPTER 3 REVIEW OF CODES AND STANDARDS 20
  3.1 Introduction 20
  3.2 New Zealand Building Regulations 1992 and Amendments 21
  3.3 New Zealand Fire Service (NZFS) Recommendation 23
  3.4 New Zealand Automatic Fire Sprinkler Standard 24
  3.5 National Fire Protection Association (NFPA) 24
  3.6 Building Code of Australia (BCA) 28

3.7 Non-Regulation Fire Protection Guidelines for Distribution Substation 29
3.8 Comparison of Transformer Fire Protection Requirements 32
CHAPTER 4 REVIEW OF TRANSFORMER FIRE 35
4.1 Introduction 35
4.2 Fire Resistance Rating of Construction 35
4.3 Evacuation in High Rise Building 36
4.4 Study on the Health Effect of Exposure to A Transformer Fire 38
4.4.1 Fitzgerald et al. (1981) 38
4.4.2 Eschenroeder & Faeder (1988) 38
4.5 Experiment on Transformer Oil Fire 40
4.5.1 Heskestad & Dobson (1997) 40
4.6 Transformer Ageing 41
4.6.1 Bartley (2000, 2002 & 2003) 41
4.7 Cost Effective Comparison between Different Types of Transformers 43
4.7.1 Goudie & Chatterton (2002) 43
4.8 Studies on the Dielectric Fluids 44
CHAPTER 5 DATA COLLECTION 45
5.1 Statistical Studies 45
5.1.1 Sources of Data 45
5.1.2 Historical Case Study for Transformer Fires 46
5.1.3 Number of Distribution Substations in New Zealand 48
5.1.4 Fire Incidents Reported to the NZFS FIRS 49
5.1.5 Fire Incident Reported to the NFIRS (U.S.) 56
5.2 Reliability Data 60
5.2.1 Transformer and Associated Equipment 60
5.2.2 Fire Protection Systems 61
CHAPTER 6 FAULT TREE ANALYSIS 65
6.1 Introduction 65
6.2 Fault Tree 66
CHAPTER 7 EVENT TREE ANALYSIS 70
7.1 Introduction 70
7.2 Model Overview 73
7.3 Analysis Approach 77
7.4 Identifying the Initiating Event and the Pathway Factors 79

7.5 Structuring the Event Tree Branch Logic 79
7.6 Quantification of the Branch Line Probabilities 84
7.6.1 Initiating Event Likelihood 84
7.6.2 Smoke Detection System (SDS) 84
7.6.3 Sprinkler System (SS) 86
7.6.4 Manual Fire Service Suppression – Firefighter Action Time (FAT).... 88
7.6.5 Manual Fire Service Suppression – Manual Fire Fighting (MFF) 90
7.6.6 Wall Barrier Integrity Maintained (WBI) 92
7.6.7 Summary of the Probability Distributions for the Pathway Factors... 101
7.7 Quantification of the Consequence 105
7.7.1 Introduction 105
7.7.2 Rate of civilian fatalities and injuries 105
7.7.3 Value of statistical life 108
7.7.4 Consequence of a fire 109
7.8 Fire Risk Estimation 110
CHAPTER 8 COST-BENEFIT ANALYSIS 113
8.1 Introduction to Cost-Benefit Analysis 113
8.2 Methodology 115
8.3 Cost Analysis for the Risk Reduction Alternatives 117
8.3.1 Cost Consideration 117
8.3.2 Sprinkler System 118
8.3.3 Fire Resistance Rated Constructions (Wall barrier) 121
8.3.4 Type of Transformer 123
8.3.5 Summary of the Cost Estimate 125
8.4 Risk Reduction Benefit Cost Ratio 126
8.5 Discussion 129
CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS 132
REFERENCES 136
APPENDIX A: Transformer and Associated Equipment 144
APPENDIX B: Distribution Substation Fire Safety Protection Required by the NZFS........ 151
APPENDIX C: Statistical data of Transformer Fires in Distribution Substations................ 153
APPENDIX D: Calculation of the Probability of Manual Fire Fighting Performance.......... 158
APPENDIX E: Probability Distribution of the Total Risk for each scenario 159
APPENDIX F: Calculation of the Cost Benefit Ratio 173

LIST OF FIGURES

Figure 2-1: Typical electrical power network 8
Figure 2-2: Schematic drawing of typical transformer 11
Figure 2-3: Fault tree for the transformer fault 18
Figure 4-1: Convective HRR of transformer oil with no drainage, extracted from Heskestad & Dobson (1997) 40
Figure 4-2: Convective HRR of transformer oil with drainage, extracted from Heskestad & Dobson (1997) 40
Figure 4-3: Number of transformer failures, reproduced from Bartley 2000 [52] 41
Figure 4-4: Initial cost for transformer dielectric materials, reproduced from Goudie & Chatterton (2000) 43
Figure 5-1: Number of distribution substations in New Zealand from 1946 to 2006 48
Figure 5-2: Number of distribution substation fires in 2000/06 (Source NZFS FIRS) 50
Figure 5-3: Monthly incidence of distribution substation fires in 2000/06 (Source NZFS FIRS) 51
Figure 5-4: Hourly trends for distribution substation fires in 2000/06 (Source NZFS FIRS) 51
Figure 5-5: Causes of distribution substation fires (Source NZFS FIRS) 52
Figure 5-6: Object first ignited (Source NZFS FIRS) 53
Figure 5-7: Equipment involved (Source NZFS FIRS) 54
Figure 5-8: Source of ignition (Source NZFS FIRS) 54
Figure 5-9: Extent of flame/ smoke damage (Source NZFS FIRS) 55
Figure 5-10: Number of structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 (Source NFIRS) 56
Figure 5-11: Civilian injuries as a result of structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 (Source NFIRS) 58
Figure 5-12: Civilian deaths as a result of structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 (Source NFIRS) 58
Figure 5-13: Directly property damage as a result of structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 (Source NFIRS) 59
Figure 5-14: Typical failure rates for various equipment (Extracted from Fig. 11.1 of Moss [30]) 60
Figure 6-1: Fault tree for the transformer fire 68
Figure 6-2: Fault tree for transformer internal overheat 69
Figure 6-3: Fault tree for transformer external overheat 69
Figure 7-1: Structure of the event tree for a transformer fire in a distribution substation 80
Figure 7-2: Probability distribution of the performance of smoke detection systems 85
Figure 7-3: Probability distribution of the performance of sprinkler system 87
Figure 7-4: Probability distribution of FAT – success (P_{FAT_S}) 89
Figure 7-5: Probability distribution of FAT– failure (P_{FAT_F}) 89
Figure 7-6: Probability distribution of equivalent time for transformer with mineral oil 98
Figure 7-7: Probability distribution of equivalent time for transformer with silicone oil 99

Figure 7-8: Probability distribution of equivalent time for transformer with dry type dielectric material 100
Figure 8-1: Basic components of the sprinkler systems in the distribution substation 119
Figure 8-2: Estimated total risk of the alternatives and their corresponding B/C ratio 130

LIST OF TABLES

Table 3-1: Fire safety precautions from Table 4.1 of the C/AS1 ... 23
Table 3-2: NFPA/Wales regulations liquid classification scheme ... 27
Table 3-3: Summary of the general fire protection requirements for a distribution substation in a typical residential and commercial mixed-use building ... 32
Table 3-4: Summary of the specific fire protection requirements for flammable liquid insulated transformers in a distribution substation ... 33
Table 3-5: Summary of the specific fire protection requirements for less flammable liquid insulated transformers in a distribution substation ... 33
Table 3-6: Summary of the specific fire protection requirements for Askarel/ non-flammable liquid insulated transformer in a distribution substation ... 34
Table 3-7: Summary of the specific fire protection requirements for dry type transformer in a distribution substation ... 34
Table 4-1: Properties of transformer dielectric fluid: Typical Values/ Limits ... 44
Table 5-1: Life safety consequence of distribution substation fires between 1980 and 2002 reported to the NFIRS ... 57
Table 5-2: Failure rate for transformer and associated equipment and some fire protection systems ... 61
Table 5-3: Reliability of smoke detection systems ... 63
Table 5-4: Reliability of Sprinkler systems ... 64
Table 7-1: Model building characterisation ... 73
Table 7-2: Specifications of the distribution substation ... 74
Table 7-3: A brief description of the fire protection systems combination for each scenario ... 78
Table 7-4: A brief description for each of the 14 outcome events ... 81
Table 7-5: Summary of the probability distribution of the performance of smoke detection systems ... 85
Table 7-6: Summary of the probability distribution of the performance of sprinkler system ... 87
Table 7-7: Probability that t_{a_a} less or more than 10 minutes ... 88
Table 7-8: Summary of the probability distribution of firefighters' action time ... 90
Table 7-9: P_{MFF} in general buildings ... 90
Table 7-10: Probability distribution of manual fire fighting performance ... 91
Table 7-11: Input parameters and values for determining the fire load density ... 95
Table 7-12: Input parameter and values for determining the ventilation factor ... 96
Table 7-13: The input probability distributions for the calculation of equivalent time ... 97
Table 7-14: Summary of the probability distribution of wall barrier integrity maintained (P_{WBI}) ... 100
Table 7-15: Overall summary of the probability distributions for the pathway factors ... 102
Table 7-16: Rate of casualties in residential apartment and retail areas with various combinations of fire safety systems ... 106
Table 7-17: Rate of casualties per fire in the model building with various combinations of fire safety systems for each outcome event. ... 107
Table 7-18: EMV for the life safety consequence of each outcome events ... 109
Table 7-19: summary of the statistical values of the total risk (NZD$/fire incident) for each scenario ... 111
Table 8-1: Cost of sprinkler systems in the distribution substation ... 120

Table 8-2: Initial costs and annual costs of sprinkler systems 120
Table 8-3: Cost of the FRR constructions 121
Table 8-4: Initial costs and annual costs of the FRR construction 122
Table 8-5: Cost of different types of transformer 124
Table 8-6: Initial costs and annual costs of different types of transformers 124
Table 8-7: Summary of initial costs and annual costs (Mean value only) 125
Table 8-8: A summary of the results of the B/C ratio calculation 127
Table 8-9: Ranking of the B/C ratios with Scenario 1 as the base case 128
Table 8-10: Ranking of the B/C ratios with Scenario 4 as the base case 128
Table 8-11: Ranking of the B/C ratios with Scenario 7 as the base case 128
Table 8-12: The ranking for the fire safety design options required in the standards and guidelines 129

CHAPTER 1 INTRODUCTION

1.1 Impetus for Research

Nowadays, electricity has become part of our life. Lighting, air conditioning, heating, computers, phones and cooking appliances, these power consumers can be easily found around us. According to the annual report 2004/ 2005 by Transpower New Zealand Ltd. [4], each New Zealand household uses about 8.12kWh per day in average and the power consumption is increasing each day.

Generally, a 750kVA transformer can support about 60 to130 families or shops depending on the weather, the season, the number of occupants and the power usage of occupants. Due to the increasing population and higher loading density in New Zealand each year, more and more high-rise buildings are built. Typically, a high-rise building containing more than 40 families or shops is likely to have their own transformer installed inside or adjoined to the building. In this case, the fire safety design of distribution substations may become an important issue to be addressed for minimising the potential risk to the members of public.

Currently, three types of transformers are commonly used in the market. These include (1) dry type transformers; (2) less flammable liquid insulated transformers and (3) flammable liquid insulated transformers. Dry type transformers are transformers containing solid or gas insulation material. The fire hazard of dry type transformers is generally considered to be low compared to liquid type transformers due to the limited amount of combustible materials present in the transformers. For liquid type transformers, less flammable liquid is expected to have a high fire point (above 300°C) and hence, is more difficult to ignite (Refer to Section 4.8). From a fire hazard point of view, transformers insulated with flammable liquid is considered to have the highest fire hazard out of the three types of transformers due to the combustible liquid oil present and their relatively lower fire point (100°C to 170°C).

From the literature, it is understood that transformers are reliable. Failure of transformers as a result of fire is considered to be very unlikely. However, once transformer fire occurs, the potential impact on life safety, property and the environment would be very high. This phenomenon is recognised as a low frequency and high consequence event.

Fire risk is generally measured based on the size of the fire loads in the designated area. In distribution substations, the fire load density may vary significantly depending on the types of transformers. For example, distribution substation consists of a dry type transformer is expected to have low fire load density, including power cables and electrical components, and hence, the fire risk in the distribution substation is low. On the other hand, when distribution substation consists of a liquid type transformer, high fire load density is expected due to the presence of transformer oils. In this case, the fire risk in the distribution substation is considered to be high. The ranking of different transformer types with respect to the fire risk is shown in ascending order as follow:

1. Low risk: Distribution substation consists of dry type (e.g. dry air) transformers and associated electrical equipment
2. High risk: Distribution substation consists of less flammable liquid (e.g. silicone oil) insulated transformers and associated electrical equipment
3. Very high risk: Distribution substation consists of flammable liquid (e.g. mineral oil) insulated transformers and associated electrical equipment

In New Zealand, a compliance document (C/AS1) [3] for fire safety is developed by the Department of Building and Housing. This compliance document describes solutions for a wide range of buildings deemed to comply with the New Zealand Building Code (NZBC) [5]. Fire safety design must be accepted by the Building Consent Authority if it satisfies the provisions of the compliance document. However, the requirements of fire safety protection systems for distribution substations are not stated in this compliance document. Therefore, the New Zealand Fire Service (NZFS) has produced a list of fire safety protection requirements for distribution substations in a letter, dated 10th July 2002. The list of fire safety protection requirements for distribution substations proposed by the NZFS is shown in Appendix B.

A review by Nyman [1], has considered the fire safety requirements proposed by the NZFS and discussed the issues with a number of fire engineers over the last three years. Nyman has spoken to the NZFS and he found that the NZFS fire safety requirements for distribution substations are proposed on the basis of a review of their experience and knowledge accumulated over the years. However, there has been no significant study conducted in this fire safety requirement development. Nyman concerned that one of the requirements regarding the four hour fire separation between the distribution substation and the interior spaces of the building may not be necessary when considering the risk exposure to the building occupants in different situations, such as the involvement of the sprinkler systems and the use of transformers with a lower fire hazard. As a result, the correct approach to the fire safety design of distribution substations has become a subject of debate between stakeholders, without agreement on the appropriate level of fire protection for the risk posed by transformer installation.

Indoor distribution substations are often recommended to be located on the ground level, providing direct access to outside the building, and to be fire separated from the interior spaces of the building. Internal access may or may not be provided depending on the site restriction. The potential hazard of transformer fires to the building occupants is that the fire and smoke may spread out of the distribution substation through the separation due to construction failure, improper sealed penetration or leakage through the doorway. Hence, it is important to control or confine the transformer fire and smoke to the room in order to provide sufficient time for the building occupants to escape safely without exposing them to any untenable conditions.

This research conducts a Quantitative Risk Assessment (QRA) of a transformer fire in a typical New Zealand high-rise residential and commercial mixed-use building when different fire safety designs and transformer types are applied to the indoor distribution substation. At the conclusion of the report, a recommendation on the most appropriate fire protection systems for an indoor distribution substation will be provided as a result of the cost-benefit analysis. The cost-benefit ratios are measured based on the Equivalent Monetary Value of the fire risk reduction, with respect to the costs of the combinations of the fire safety systems for the alternative cases, from its respective base case. Note that in this research the cost-benefit analysis does not consider property damage, loss of business or environment damage due to transformer fires and the fire suppression.

1.2 Objective of this Research

The primary objective of this research is to evaluate whether the four hour fire separation between distribution substations and the interior spaces of the building proposed by the NZFS is a cost-effective solution to safeguard occupants from injury or illness in the event of a transformer fire in a typical New Zealand high-rise building. The following work statements were formulated to accomplish this objective:

- Examine and summarise the national and international regulation standards and non-regulation guidelines for the fire safety design of distribution substations;
- Study the fundamental theory of transformers and the like, such as transformer failure protection systems, dielectric fields, etc;
- Examine and summarise the characteristics of historical incidents and data for transformer fires in distribution substations;
- Examine and summarise the reliability of active fire protection systems, such as sprinkler systems and smoke detection systems;
- Analyses and estimate the transformer fire risks in different scenarios using Quantitative Risk Analysis, such as Event Tree Analysis;
- Analyses and estimate any cost benefit of the alternative fire safety designs;
- Propose appropriate fire safety designs of distribution substations in a typical New Zealand high-rise residential and commercial mixed-use building.

1.3 Scope of this Research

The scope of this research is to evaluate the feasibility and effectiveness of the proposed fire safety design solutions to the building occupants' safety only. Assumptions and limitations made for this research are illustrated as follow:

General:

- Deflagration and detonation may cause room-boundary failure. However, it is beyond the scope of this study.
- Property damage, loss of business or environment damage due to transformer fires and the fire suppression is not a subject of this study.
- Transformers are assumed to be the first item ignited in the distribution substation.
- Where uncertainties are not considered explicitly, conservative assumptions are made.

Source of data :

- Accuracy of data may significantly affect the output of this assessment. Fire incident data recorded to the Fire Incident Reporting System (FIRS) between 2000 and 2006 is provided from the NZFS and is used for the assessment in this research. Uncertainty may be introduced to this data during data collection, manipulation and the application of the data
- Due to the lack of information on the reliability of sprinkler systems and smoke detection systems specifically for distribution substations, reliability of sprinkler systems and smoke detection systems for general buildings has been used instead.
- An appropriately designed sprinkler system should be able to provide early fire suppression in cases of a fire and reduce the fire size and growth rate. Therefore, this assessment assumes a transformer fire is to be controlled and confined in the room once the sprinkler system is activated.

1.4 Report Outline

This report consists of eight chapters:

Chapter 2 provides a background study, which includes a brief description of the power network system and the fundamental theory of transformer systems. It also summarises the potential failure of transformers and the failure of fire safety protection systems.

Chapter 3 provides a review of the literature with respect to the subject of this research. The national and international regulation standards and non-regulation guidelines for the fire safety design of distribution substations are summarised. A review of other relevant articles and papers is also included in this chapter.

Chapter 4 provides the historical data analysis for distribution substation transformer fires. This chapter also discusses the reliability of sprinkler systems and smoke detection systems.

Chapter 5 provides a fault tree analysis of transformer fire.

Chapter 6 provides a Quantitative Risk Analysis (QRA) for a transformer fire initiating in a distribution substation. This includes the methodology of the analysis, event tree analysis and discussion of the results.

Chapter 7 provides a cost-benefit analysis of the risk reduction alternatives. This includes the methodology of the analysis, cost-benefit analysis and discussion of the results. The initial costs and annual costs of sprinkler systems, different types of transformers and the FRR construction are also provided.

Chapter 8 provides the conclusions and findings of the research. Recommendations and future work are also discussed.

CHAPTER 2 BACKGROUND

2.1 Electrical Distribution

2.1.1 Power Generation

In New Zealand, power is primarily generated from three energy sources. These are (1) Hydro; (2) Thermal (natural gas and coal fired) and (3) Geothermal power generation. Hydro-power is the dominant source of electricity generation in New Zealand. Depending on the weather conditions, typically 60% to 70% of all electricity is produced by hydro power generation, about 24% by thermal (natural gas and coal fired) stations and the rest by geothermal stations as mentioned by Contact Energy Ltd. [6], Genesis Energy Ltd. [7] and Meridian Energy Ltd. [8]. In addition to the power generation, some renewable resources also are used to produce a small amount of power, such as wind power generation.

2.1.2 Electric Power Transmission

Electric power is normally generated in a power station at 11 to 25kV. In order for the transmission lines to carry the electricity efficiently over long distances, the low generator voltage is increased to a higher transmission voltage by a step-up transformer, i.e. 400kV, 220kV or 110kV as necessary. Supported by tall metal towers, lines transporting these voltages can run into hundreds of kilometres. The grid voltage is then reduced to a sub-transmission voltage, typically 33kV or 66kV, in terminal stations (known as Power substations).

Sub-transmission lines supply power from terminal stations to large industrial customers and other lower voltage terminal stations, where the voltage is stepped down to 11kV for load points through a distribution network lines. Finally, the transmission voltage is reduced to the level adapted for household use, i.e. 415V (3-phase) or 240V (1-phase) at distribution substations adjacent to the residential, commercial and small to medium industrial customers. Figure 2-1 shows a typical electrical network system, in which power is transformed to the voltages most suitable for the different parts of the system.

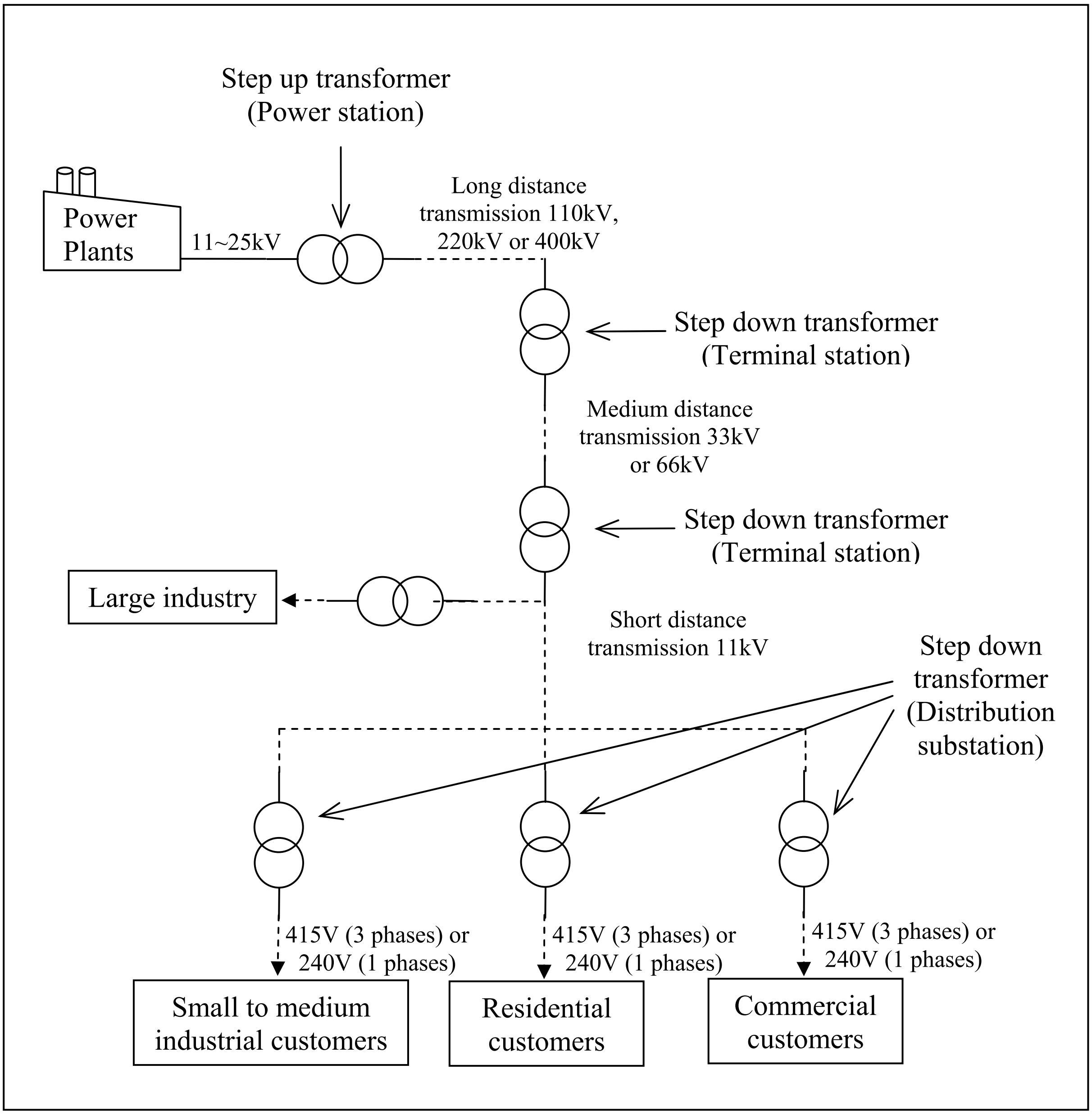


Figure 2-1: Typical electrical power network

2.2 Distribution Substation

Distribution substations are a system of transformers, meters, and control and protection devices. Although the system design may be different from one to another, the basic principle for the operation of distribution substations should be similar. In order to control, protect and monitor the system, there is usually a set of switchgears and meters on both ends of the transformer which includes a control board, High Voltage (HV) switchgear and Low Voltage (LV) switchgear. Other equipment, such as lightning arrestors and power cables, will be placed together within a typical distribution substation.

Depending on site specific constraints, distribution substations may be located outdoor; either fully exposed or in an enclosure, or in a room inside a building. A transformer fire in a residential and commercial mixed-use building may potentially expose a larger amount of people compared to an outdoor transformer fire. Therefore, this research will primarily focus on a transformer fire in a room inside a building. The regulation standards and non-regulation guidelines for the fire safety design of distribution substations are discussed in Section 1.1.

2.3 Overview of Transformers

2.3.1 General Construction of Transformers

The major components of a transformer are the coils (windings), the core, the tank or casing, the radiator, and the bushings as shown in Figure 2-2. Generally, transformer coils are made of copper because it has a lower resistance and is more efficient compared to other metals. Each winding is wrapped with an insulating material such as paper (the interturn insulation). The primary winding is usually wound around the transformer core and the secondary winding is then wound on top of the primary winding. Between each layer of the windings, another layer of insulating material is wrapped to provide extra insulation between the windings. (The information in this section is from Lin [9], Gibbs [10], Myers [11], Heathcote [12] and Zalosh [13]).

The major transformer components are briefly described below:

1) Core is a ferromagnetic material (commonly soft iron or laminated steel) that provides a path of high magnetic permeability from the primary circuit to the secondary circuit.
2) Windings allow a secondary voltage to be induced in the secondary circuit from the alternating current (AC) voltage in the primary circuit. The change in magnetic field in the transformer core caused by applying primary AC voltage causes an induced magnetic field and, hence, voltage on the secondary winding.
3) Tank or casing, which is usually a reinforced rectangular structure in these transformers, contains the dielectric material, the core and the windings.
4) Dielectric material is a substance that is a poor conductor of electricity but an efficient supporter of electrostatic fields. It can be fluid oils, dry solids or gases (see also section 2.3.3)
5) The expansion tank or conservator containing dry air or dry inert gas is maintained above the fluid level.
6) Bushing is an insulating structure that provides a conducting path though its centre, its primary function is to insulate the entrance for an energised conductor into the tank.

7) Pressboard barriers, between the coils and between the coils and core, are installed to increase the dielectric integrity of the transformer.
8) The tap changer is a connection point along a transformer winding that allows the number of turns to be selected, or so-called voltage regulating device.
9) The radiator provides a heat transfer path to dissipate the internal heat generated in the transformer.
10) The pressure relief device is used to protect the tank against excessive pressure release inside a transformer tank. (Refer to Section 2.3.4)

Usually, a nameplate with the transformer details would be attached to a side of the tank. It helps in identifying the primary coil and the secondary coil ratings, its configuration, volume of oil and the weight. Photographs of transformer and associated facilities taken from site visits to two distribution substations in Christchurch, New Zealand are shown in Appendix A.

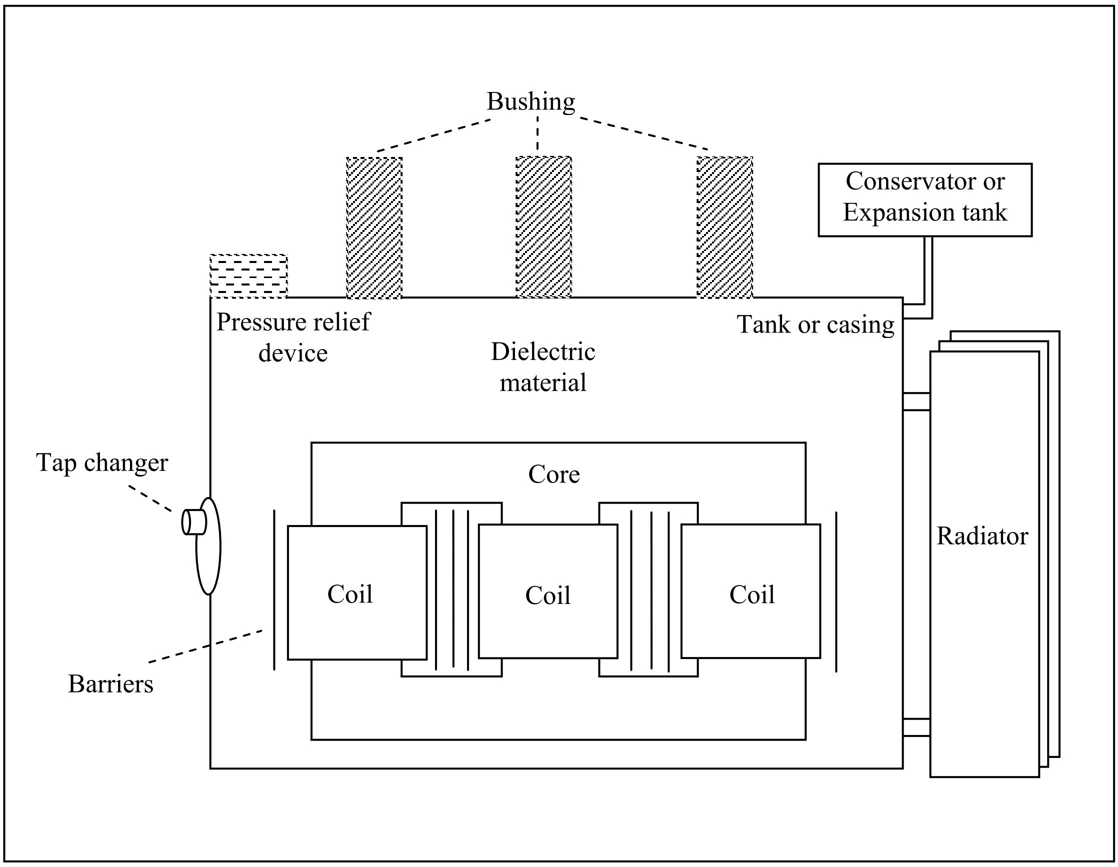


Figure 2-2: Schematic drawing of typical transformer

2.3.2 Transformer Fundamental Theory

Transformers are electromagnetic devices that change values of voltage and current without changing the frequency and the power. By controlling the number of windings, or tapping into the windings, the output voltage can be adjusted to the design level of voltage.

In a typical transformer, since all fluxes link both coils, the instantaneous induced electromagnetic fields (e.m.f) and the voltage in the various windings must be directly proportional to the numbers of turns, hence,

Equation 2-1: $$\frac{|V_1|}{|V_2|} \approx \frac{N_1}{N_2}$$

where V_1 is the primary winding voltage (v)

V_2 is the secondary winding voltage (v)

N_1 is the number of turns in the primary winding

N_2 is the number of turns in the secondary winding

On the other hand, the number of turns between the primary and the secondary windings is inversely proportional to the current in the various windings; hence,

Equation 2-2: $$\frac{|I_2|}{|I_1|} \approx \frac{N_1}{N_2}$$

where I_1 is the primary winding current (A)

I_2 is the secondary winding current (A)

As a result of substituting Equation 2-2 into Equation 2-1, an inverse relationship is found between the voltage ratio and the current ratio.

Equation 2-3: $$\frac{|V_1|}{|V_2|} \approx \frac{|I_2|}{|I_1|}$$

Connelly [14] states that at normal power frequencies of 25 to 100 cycles, it is necessary to introduce some factors which may influence the voltage-current relationship. These factors may be one of the followings:

- The winding resistance – I^2R losses in either the primary or secondary coil;
- Energy dissipation from hysteresis and eddy current in the core;
- Leakage inductance;
- Proximity effect and skin effect in windings;
- Electromagnetic radiation; and
- Effects of temperature

The abovementioned factors are the fundamental theory of the voltage and current transformation. However, transformer operation can be an individual topic. The detail design of transformers is beyond the scope of this thesis and, therefore, is not provided. The details on the principle of transformers can be found in Heathcote [12], Connelly [14], Blume [15], Bean [16] and Mathew [17].

2.3.3 Transformer Type

Transformers are designed and built for both indoor and outdoor applications. Depending on the authority, they are often classified in terms of its power rating or its cooling medium (dielectric material).

Dielectric material is a poor conductor of electricity. The purpose of using dielectric material is to insulate the current flow between the wires or the metals, preventing an unwanted conduction. In this research, a transformer power rating of 750kW is specified for the assessment. The transformer type is therefore, classified in terms of the dielectric material type rather than its power rating. Practically, there are four major types of dielectric material as follows:

- Flammable liquid (such as mineral oil)
- Less flammable liquid (fire point > 300°C, such as silicone oil and vegetable oil)
- Non-flammable liquid (such as Askarels, which is a generic name for Chlorinated Hydrocarbon insulating liquids)
- Insulating solids and gases (such as dry air)

Josken [18] states that mineral oil is a combustible material and has been the most widely used fluid for electrical insulation and heat transfer in electrical equipment for more than 100 years. The popularity of mineral transformer oil is due to its availability and its relatively low cost, as well as being an excellent dielectric and cooling medium. However, Oommen [19] has found that mineral oil has undesirable characteristics, such as a low fire point (110°C to 185°C), environmental concerns and degradation of insulation paper. Hence, many other types of dielectric material have been developed as substitutes for mineral oils.

Hallerberg [20] and Mcshane [21] state that during the 1920s, a family of liquids, the so-called Askarels, were developed to solve the combustibility problem of mineral oil. However, their use was discontinued in the late 1970s due to the fact that Askarels are commonly composed of 60% to 70% polychlorinated biphenyls (PCB's), which are now considered to be highly toxic and are an environmentally hazardous product. It is also recognised that the production and commercialisation of PCB's was officially banned in 1977 by the U.S

Environmental Protection Agency (EPA) [22]. As a result, any transformers containing Askarels have been refilled with other dielectric materials. Bracco [23] reports that some existing liquid type transformers may still contain PCB's at various concentrations, usually less than 10 parts per million (ppm), and hence, these units are often called Askarel insulated transformers. Some typical trade names for Askarel are as follows (More information of Askarel (PCB) transformer can be found in Myers [11]).

- Asbestol
- Aceclor
- Apirolio
- Aroclor
- Bakola 131
- Chlorextol
- Chlorophon
- Diaclor
- Dycanol
- Elemex
- Eucarel
- Hyvol
- Inerteen
- Kanechlor
- No-flamol
- Pyralene
- Pyroclor
- Saf-T-Kuhl
- Soviol/Sovol/Solvol
- Ugilect

Since the use of Askarel is prohibited, other high fire point liquids (also known as less flammable liquids) have been developed as the replacement fluids, such as polydimethyl-siloxane (PDMS or silicone oils), polyalphaolefins (PAO), High Molecular Weight Hydrocarbon (HMWH), Vegetable oil, etc. These dielectric fluids are formulated to withstand fairly large amounts of electrical arcing and generally have a higher fire or flash point in comparison to mineral oils. As defined by Technologies [24] and McCormick [25], less flammable liquids must have a minimum fire point of 300°C. More details about the properties of transformer dielectric fluids can be found in Section 4.8.

Dry type transformers are transformers where the core and windings are not immersed in an insulating liquid, but in either an inert gas or solid. Dry type transformers are usually larger and hotter than the liquid filled transformers with the same power rating. Due to the cost issues, dry type transformers are more frequently used in distribution substations than the power or terminal stations. In most gas insulated transformers, Sulfur Hexafluoride (SF6) gas or dry air, is often used as a cooling medium since it has an excellent dielectric strength, chemical stability, thermal stability and non-flammability as mentioned in Toda [26].

2.3.4 Potential Transformer Problems and Protections

Potential problems

As Gajic [27] stated, 70% to 80% of the total number of transformer failures are due to internal winding insulation failure. Winding insulation faults may cause a short circuit. Even if it occurs at a very small point, the energy released at that point can be large within a short time period. The energy can be large enough to melt the coils and to char or ignite the insulating material. In such cases, if the protective devices are effective, the damage can be confined to the object of origin; otherwise, a more serious and costly impact, such as fire and explosion, may result as mentioned in Hattangadi [28]. The cause of transformer failures can be classified as one of the following:

- Failure due to defects in internal connections and terminals
- Failure due to interturn insulation in the main windings
- Failure of the main insulation between the windings and the transformer tank

These failures are discussed in detail below:

Failure due to defects in internal connections and terminals:

As a result of bad connections, the contact resistance will be increased. Since the heat developed in the joint between conductors is directly proportional to the product of the square of the current and the contact resistance, the temperature of the conductors will also be increased if this occurs. A circle of increasing temperature and increasing contact power loss is established. Although there is equipment developed to protect transformers against external surge voltage, to prevent overloading or to monitor the conditions of the transformer oil, it is not practicable to detect the local overheating at defective internal connectors and terminals. When such defects occur, failure of the transformer is almost certain. Hence, the only way of preventing this failure from occurring is by taking certain precautions in the design, manufacture and installation of the transformer.

Failure due to interturn insulation in the main windings:

Bartley [29] states that interturn insulation faults, such as the paper wrapping, are most likely as a result of the degradation due to thermal, electrical and mechanical stress or moisture. The main cause for the interturn insulation failure (insulation breakdown) is due to damage to the paper insulation or to the loose spacers dropping out. Such defects may occur due to one of the following reasons:

- Physical damage caused by constant abrasion with the flowing oil and the substances in the fluid
- Damage caused by thermal damage due to excessive oil temperature
- Degradation of insulation material properties during exposure to moisture (absorbed from oils)
- Paper insulated conductors that have sharp edges on the corners may get shorted during service under the effect of vibration, thermal expansion and contraction, movements caused by electromagnetic force or even the static assembly force between the coils

Degradation or damage of interturn insulation causes an insulation breakdown between turns or layers. As a result of insulation breakdown, a high-impedance low-current fault develops in the windings. At this point, if the protection systems do not quickly detect the fault and isolate the transformer from the power grid immediately, the fault current will continuously increase due to decreasing coil impedance and the constant power supply ($P = IR^2$). The high current will result in an electrical breakdown in the transformer oil and so-called arcing. The arc decomposes and vaporises the oils and causes the formation of gas bubbles. These gas bubbles will cause the liquid pressure in the confined tank to increase. If the rate of pressure increase exceeds the capability of the pressure relief device and other protection devices are not properly functioning, overpressure may rupture the tank. The escaping gas and liquids may ignite and fire may result.

Failure of the main insulation between the windings and the transformer tank:

There are two main insulation layers between the windings and the transformer tank which are the mass of the dielectric fluid and the liquid impregnated paper-board laminates. The failure of the main insulation can be avoided by providing an adequate clearance between the windings and the transformer tank. Such defects are rare due to the insulation being inspected during the regular maintenance process and any obstructions or failures can be easily verified visually.

Hence, a fault tree of transformer failure has been developed as illustrated in Figure 2-3.

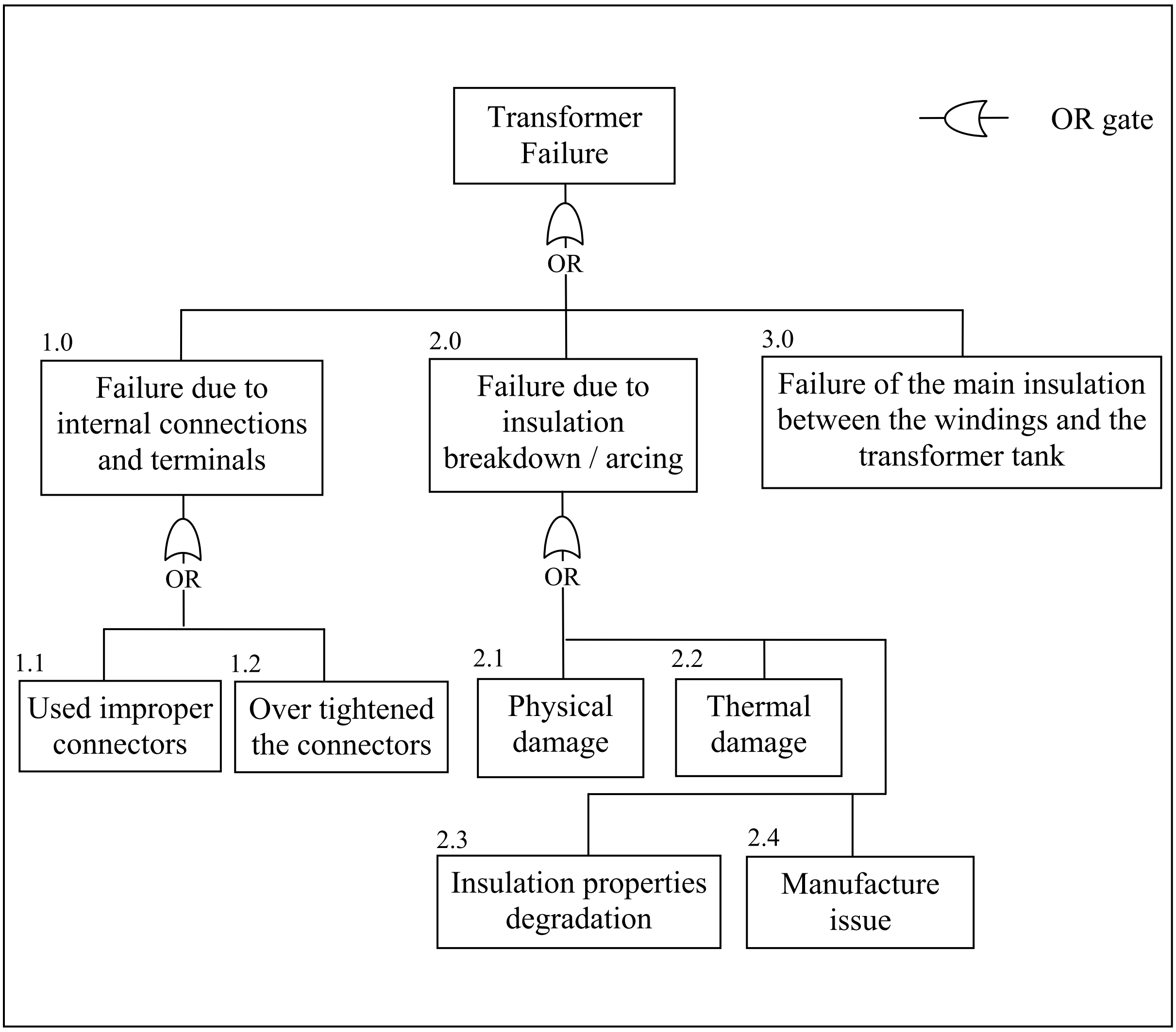


Figure 2-3: Fault tree for the transformer fault

Furthermore, transformer ageing has not been classified as the cause of failure above. However, it should be noted that the ageing of the insulation reduces both the mechanical and dielectric-withstand strength. William H. Bartley, who is a senior member of Institute of Electrical and Electronics Engineers (IEEE), has been looking into this particular issue since 2000. Some of his published work is reviewed in Section 4.6.1.

Electrical Protections

Transformers are reliable devices which have low electrical failure rates. Moss [30] states that the failure rate of distribution transformers is 0.02 to 16 failures per 10^6 operation hours, which is about 180 x 10^{-6} to 140 x 10^{-3} failures per year. However, transformer faults are considered as a low frequency and high consequence events, explosion and fire may cause catastrophic damage to property and high numbers of casualties. Depending on the required level of safety and the economic factors, the level of transformer protection may be varied. The general electrical devices used to protect against transformer faults are listed below:

1) Circuit breaker or fuses: provides protection for both internal and external faults and limitation of fault current level
2) Thermal device (thermal relay): monitors the liquid (windings) temperature and operates when it exceeds a predetermined value
3) Overcurrent relay: operates when there is a short circuit between phases or between phase and ground.
4) Liquid level gauge: measures the insulating liquid level in the tank
5) Differential relay: operates when the difference between the primary and secondary side current is over the predetermined value.
6) Lightning arresters: prevents high voltage surges in the system
7) Pressure relief device: reduces excessive pressure created by arcing
8) Sudden pressure relay: operates when it detects the accumulation of pressure in the tank
9) Gas and oil actuated (Buchholz) relay: operates when it detects the accumulation of gas in the tank

CHAPTER 3 REVIEW OF CODES AND STANDARDS

3.1 Introduction

This chapter studies the prescriptive fire safety solutions for distribution substations in different countries, such as the acceptable solution (C/AS1) in New Zealand, the Building Code of Australia (BCA) and the NFPA in U.S. In addition to the safety requirements, non-regulation guidelines from other stakeholders, such as fire service, electrical engineering organisation, insurance companies and electricity providers, are also reviewed in this section.

The main purpose of this standards and guidelines review section is to summarise the fire safety requirements for distribution substations recommended by different authorities and industries and to compare them with the requirements proposed by the NZFS. It should be noted that due to the lack of information provided by these stakeholders, the detail studies on the fundamental concepts and theoretical foundations of these requirements are not provided in this research.

3.2 New Zealand Building Regulations 1992 and Amendments

As the regulatory objective, all buildings in New Zealand must comply with the New Zealand Building Code (NZBC), which is a schedule to the Building Regulations 1992 and the subsequent amendments [5]. The NZBC is a performance based code which has mandatory provisions to comply with The Building Act 2004. Out of the 37 performance clauses in the Building Regulations, there are four relevant clauses to the fire safety in buildings. These are:

- C1 - “Outbreak of Fire”,
- C2 – “Means of Escape”,
- C3 – “Spread of Fire” and
- C4 – “Structural Stability during Fire”.

A compliance document (C/AS1) [3] is developed by the Department of Building and Housing. It is one way to satisfy the performance requirements of the NZBC. However, the fire safety design of distribution substations is not clearly specified in the C/AS1. Relevant clauses to the model building as defined in Section 7.2 are discussed below:

Purpose groups and Fire Hazard Category (FHC)

Residential apartment, which is a space for sleeping, is defined as being purpose group SR and the FHC is one as per Table 2.1 of the C/AS1. Retail shop, which is a space for selling goods, is defined as being purpose group CM and the FHC is two as per Table 2.1 of the C/AS1.

Vector Ltd [31] states that distribution substations shall be considered as a space for providing intermittently used support functions, known as purpose group ID within the C/AS1. According to the Fire Engineering Design Guide [32], a typical power station and transformer winding occupancy has a fire load of 600MJ/m^2. This fire load density is equivalent to FHC of two as described in the C/AS1 Clause 2.1.3.

Fire safety precautions

The relevant clauses of the C/AS1 are listed below:

Clause 4.5.11– “*Where any upper floor contains a sleeping purpose group, all floors below shall have an appropriate alarm system which shall activate alerting devices in all sleeping areas within the building. …For SR purpose group where any lower floor contains a purpose group other than SR, all lower floors shall have heat or smoke detectors or sprinklers (Types 3, 4 or 6).*” (See below for descriptions of the fire safety precautions types)

Clause 6.2.1 – “*Where adjacent firecells on the same floor level are permitted by Table 4.1 to have a F rating of F0, they shall be fire separated from one another. The fire separations shall have a FRR of no less than that required by Part 6 or Part 7 (for a specific purpose group or situation), or 30/30/30, whichever is the greater.*”

Clause 6.8.1 – “*Purpose Groups SR – Every household unit in purpose group SR shall be a single firecell separated from every other firecell by fire separations having a FRR derived from the F rating in Table 4.1/5, or 30/30/30, whichever is the greater.*”
Clauses 6.11.1 –“*Firecells in which ID is the primary purpose group, shall meet the same fire safety precautions as specified in Table 4.1 for purpose group WM, and shall be separated from adjacent firecells by fire separations having a FRR of no less than 60/60/60.*” (Purpose group WM is a spaces used for working business or storage with medium fire load and slow/medium/fast fire growth rates).

Clause 6.11.4 –“*Where plant is contained in a building separated by 3.0 m or more from any adjacent building, only Paragraph 6.11.3 c) shall apply.*”

Clause 6.11.3 (c) –“*Its floor level no lower than the ground level outside the external wall if gas is the energy source.*” (It should be noted that substation is a plant room but the flammable liquid is not used as an energy source. Hence, Clause 6.11.3 (a) and (b) is not applicable.)

Depending on the purpose group, the FHC, the escape height and the occupant load, the fire safety precautions for the firecell can be found from Table 4.1 of the C/AS1. Table 3-1 shows the fire safety precautions for purpose group SR, CM and WM (the same fire safety precautions are required for purpose group ID as per Clause 6.11.1 of the C/AS1).

Table 3-1: Fire safety precautions from Table 4.1 of the C/AS1

Firecell	Residential apartment levels	Retail shops	Distribution substation
Purpose group	SR	CM	WM (ID)
FHC	1	2	2
Escape height	10m - 25m	0m	0m
Occupant load	Less than 40 occupants	Less than 100 occupants	Less than 100 occupants
Fire Safety Precaution	FRR of 45/45/45 (Table 4.1/5 & Clause 6.8.1)	FRR of 30/30/30 (Table 4.1/1 & Clause 6.2.1)	FRR of 60/60/60 (Clause 6.11.1)
	Type 4 (Table 4.1/5)	Type 3, 4 or 6 (Clause 4.5.11)	Type 3, 4 or 6 (Clause 4.5.11)
	Type 14 (Table 4.1/5)	Type 2 (Table 4.1/1)	Type 3 (Table 4.1/1)
	Type 16 (Table 4.1/5)	Type 18 (Table 4.1/1)	Type 16 (Table 4.1/1)
	Type 18 (Table 4.1/5)		Type 18 (Table 4.1/1)

Where Type 2 = Manual fire alarm system
Type 3 = Automatic fire alarm system with heat detectors and manual call point
Type 4 = Automatic fire alarm system with smoke detectors and manual call point
Type 6 = Automatic fire sprinkler system with manual call point
Type 14 = Fire hose reel
Type 16 = Emergency lighting in exitways
Type 18 = Fire hydrant system

3.3 New Zealand Fire Service (NZFS) Recommendation

An interpretation of distribution substation fire protection requirements was made by the NZFS in a letter, dated 10th July 2002. This letter is reproduced in Appendix B. Issue two states that the construction separation between the distribution substation and the interior spaces of the building, including ceiling and floor, shall have FRR construction of no less than four hours. It goes on to state that distribution substations, the exterior access shall have a minimum clear opening area of 800 x 2100mm wherever possible and that if the building is a non-sprinklered building, no sprinkler system is required in the distribution substation but heat detectors are recommended.

3.4 New Zealand Automatic Fire Sprinkler Standard

New Zealand Automatic Fire Sprinkler Standard NZS 4541:2003 [33] is the standard for the installation of sprinkler systems in New Zealand. As specified in Clause 203.5.2, sprinkler systems are required for liquid type transformers within building. For liquid type transformers, sprinkler systems are required to provide a design density of discharge of at least 10 mm/min over all transformer surfaces. From Table 2.1 of NZS 4541:2003, dry type transformers may fall into an ordinary hazard group one or two (OH1 & OH2) based upon an occupancy classification of either industrial or commercial plant rooms or electricity generation and distribution. The required sprinkler systems design density of discharge for dry type transformer is 5mm/min at minimum.

3.5 National Fire Protection Association (NFPA)

The National Fire Protection Association (NFPA) is an international organisation (U.S. based) established in 1895. It has developed a series of recommendations or standards providing design advice on fire, electrical and life safety to the public. The recommendations, codes and standards produced by the NFPA that may apply to transformer fire protection and associated electrical facilities are shown below:

- NFPA 70, National Electrical Code (NEC): Article 450-Transformers and Transformer Vaults 2005 Edition
- NFPA 850, Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations 2005 Edition
- NFPA 13, Standard for the Installation of Sprinkler systems 2002 Edition
- NFPA 15, Standard for Water Spray Fixed Systems for Fire Protection 2001 Edition
- NFPA 25, Standard for the Inspection, Testing and Maintenance of Water-Bases Fire Protection System 2002 Edition
- NFPA 30, Flammable and Combustible Liquids Code 2003 Edition
- NFPA 220, Standard on Types of Building Construction 2006 Edition

NFPA 70 National Electrical Code (NEC) [34]

The National Electrical Code (NEC) is a safety standard for the installation process of electrical systems. The fire safety design for different types of transformers, such as dry type, less flammable liquid insulated, non-flammable liquid insulated, Askarel insulated and oil insulated transformer, are covered in Article 450. The relevant clauses in relation to distribution substations are extracted from this standard and re-written as follow:

Clause 450-21 b) & c) Dry type transformers installed indoors
Individual dry type transformer of more than 112.5kVA shall be installed in a transformer room (distribution substation) of fire resistant construction with a minimum FRR of 1 hour. For dry type transformer up to 35,000 volts, no transformer vault is required, where the characteristic of the transformer vault are specified in part 3 of Article 450.

Transformer Vault: Part 3 of Article 450 states that the minimum fire resistance for the transformer vault construction, such as walls, roof, floor and doorway, should have a FRR of no less than 3 hour or it can be reduced to 1 hour FRR if an automatic sprinkler suppression system, water spray, carbon dioxide or halon, is installed. In addition to the requirements, only qualified persons are allowed to access the transformer vault. Ventilation systems are required in this case, in which an automatic closing fire damper shall also be included. If natural ventilation is used, the combined net area of all ventilating openings shall be not less than 1900mm^2 per kVA of transformer capacity in service (1.425m^2 for a 750kVA transformer). Practically, a concrete wall with overall thickness of 211mm and 311mm shall have 3-hour and 4-hour fire resistance, respectively. Note that transformer vault in the NEC may imply they are distribution substations as defined in this research.

Clause 450-23) Less flammable liquid insulated transformers installed indoors:
If the transformer is up to 35,000 volts, no transformer vault is required. Indoor installations shall be permitted with one of the following cases: (Note that less flammable liquid means the liquid has a fire point of not less than 300°C)

Case 1:	- In Type I and Type II buildings - As stated in Clause 4.3 of NFPA 220 [35], both Type I and Type II building structural components are non-combustible or limited combustible materials. The difference between Type I and Type 2 building is that the entire construction of Type I building must have fire rating of no less than 90 minutes except the interior and exterior non-load bearing walls, while Type II construction may not have any FRR construction. - In areas which no combustible materials are stored; - Provided a liquid confinement area;
Case 2:	- Provided with an automatic fire extinguishing system - Provided a liquid confinement area
Case 3:	- In accordance with Clause 450.26 as described below (Installed in a transformer vault).

Clause 450-24) Non-flammable liquid insulated transformers installed indoors:
If the transformer is up to 35,000 volt, no transformer vault is required but a liquid confinement area and a pressure relief vent shall be provided.

Clause 450-25) Askarel insulated (PCB contaminated) transformers installed indoors:
If the transformer is up to 35,000 volt, no transformer vault is required. Pressure relief vent should be provided for transformer rated over 25kVA.

Clause 450-26) Oil insulated transformers installed indoors
This type of transformers should be installed in a transformer vault.

NFPA 850 Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations [36]

Clause 5.2.5 of the NFPA 850 states the design criteria regarding the fire protection systems for distribution substations. These recommendations are in relation to Clauses 450-26 of NFPA 70. For oil insulated transformers containing more than 379 L of oil, a construction having a FRR of no less than 3 hour shall be used for the transformer vaults or it can be reduced to 1 hour FRR if a sprinkler system is installed.

Dry type transformers are suggested for indoor installations under this document. Openings in fire barriers are mentioned in Clause 5.2.2, it states that "*All openings in fire barriers should be provided with fire door assemblies, fire dampers, through penetration seals (fire stops), or other approved means having a fire protection rating consistent with the designated fire resistance rating of the barrier…*". Moreover, in an area containing switchgears and relays, smoke detectors are required under Clause 7.8.4.

NFPA 30 Flammable and Combustible Liquids Code [37]

According to Clause 3.3.25 of NFPA 30, liquids can be classified based on their flash points as shown in Table 3-2. Additionally, the liquid classification scheme from the Hazardous Waste (Wales) Regulations 2005 [38] is also included in the table for comparative purpose. Note that typical mineral oil have the lowest flash point at 100°C; it is therefore considered as a Class III combustible liquid.

Table 3-2: NFPA/Wales regulations liquid classification scheme

	Liquid classification	Flash point range
NFPA - Class I	Flammable liquid	< 37.8°C
NFPA - Class II	Combustible liquid	> 37.8°C and < 60°C
NFPA - Class III	Combustible liquid	> 60°C
Wales regulation	Highly Flammable liquid	< 21°C
Wales regulation	Flammable liquid	> 21°C and < 55°C

NFPA 13 The Installation of Sprinkler systems [39] / NFPA 15 Water Spray Fixed Systems for Fire Protection [40] / NFPA 25 Inspection, Testing and Maintenance of Water-Bases Fire Protection System [41]

According to Clause 5.4 and Clause 13.31.1 of NFPA 13, distribution substations shall be categorised as Extra Hazard Group 2 occupancy. For a mineral oil insulated transformer, automatic sprinkler suppression systems with discharge density of 10.2mm/min covering area up to 325m^2 are required. The installation of nozzles is required in NFPA 15 to cover areas where spills may travel or accumulate. NFPA 25 provides detailed criteria to be followed when fire protection systems are damaged.

3.6 Building Code of Australia (BCA)

The BCA is a prescriptive standard in Australia. In clause C.2.13 (a) and (b) of the BCA, an electricity substation and a main switchboard located within a building (known as an distribution substation in this research) must –

(i) be separated from any other part of the building by construction having a fire resistance level of not less than 120/120/120 and;
(ii) have any doorway in that construction protected with a self-closing fire door having a fire resistance level of not less than -/120/30.

In the Building Code of Australia, the fire safety precaution is dependent on the type of building, and the escape height and floor area of the compartment. In cases where distribution substation is installed in a high-rise residential and commercial mixed-use building having an escape height of less than 25m and the floor area of less than 2,000m^2, an automatic smoke detection and alarm systems and sprinkler systems are required.

3.7 Non-Regulation Fire Protection Guidelines for Distribution Substation

Many stakeholders, such as electrical engineering organisation, insurance companies and electricity providers, have developed their own guidelines applicable to the fire protection of distribution substations. These guidelines have been widely used by many industries as references to select the fire protection systems for distribution substations. Four guidelines are examined in this research. Note that as required by the electricity providers for commercial purposes, the names of the companies are not given in this research.

Institute of Electrical and Electronics Engineers (IEEE)

IEEE is an international organization that develops standards for electronic and electrical technologies. An IEEE standard, IEEE 979-1994[42], related to substation fire protection is examined. IEEE 979-1994 is a revision of IEEE 979-1984. The title of the standard is “IEEE Guide for Substation Fire Protection”, in which the fire protection for distribution substations is described in Clause 9.1 through Clause 9.6.

In this guideline, low smoke cables are recommended for use in distribution substations. Unless installed cables comply with the flame test parameters specified in IEEE Standard 383-1974 and are properly sealed to the fire rated barriers, the cables shall be installed in trays or trenches cast with removable metal or fire-retardant material coverings. As stated in Clause 9.3, the use of oil filled equipment inside a building is not recommended. If it is used, it shall be installed in transformer rooms (distribution substations) or vaults constructed with a fire rating sufficient to withstand the largest possible fire that may occur, and a minimum of two exits is expected. However, the fire ratings for transformer vault construction are not provided in this standard. In addition to the fire safety protection system, fixed fire extinguishing systems and oil containment are recommended in this standard.

Factory Mutual Insurance Company (FM Global):

FM Global is a U.S. based insurance company, which provides property insurance protection for commercial and industrial risk and risk management services. One of their datasheets, FM Global Property Loss Prevention Datasheet 5-4 (2005), provides the fire protection guidelines for substations. FM Global is known as a Highly Protected Risk (HPR) insurer; their design criteria have been established not only to the fire exposure of a transformer, but also the potential damage to the transformer and the possible business interruption effects that a transformer fire can cause. Some loss histories are also covered in the datasheet.

As recommended in the datasheet, indoor transformers shall have a minimum of 0.9 m separation from the building walls. Smoke detection and fire alarm systems that are connected to the Fire Service and the electrical providers shall be installed in distribution substations. An appropriately designed mechanical ventilation system is also required. More specifically, the datasheet also provides the specific fire protection requirements for different types of transformers installed, which are listed as follow:

For oil insulated transformers containing more than 378.5 litres of oil, the transformer rooms (distribution substations) shall have at least one external wall and the constructions shall be fire rated with a minimum of 3 hour FRR or it can be reduced to 1 hour FRR if an automatic sprinkler system with discharge density of 15 mm/min over the room area is installed.

For less flammable liquid insulated transformers, the transformer room (distribution substation) shall be constructed with a minimum of 1 hour FRR or sprinkler systems with a discharge density of 10 mm/min over the transformer room (distribution substation) is required to be installed.

For dry type transformers, there are no specific fire protection requirements more than keeping the transformers away from other combustible materials by a non-combustible barrier or a distance of 1.5 m horizontally and 3 m vertically. However, air-cooled transformers are recommended to be in a pressurised room when they are exposed to dusty or corrosive atmospheres.

Askarel insulated transformers containing more than 50 ppm PCB’s are not allowed under this organisation; hence, a liquid replacement is required when the PCB concentration is more than 50 ppm. Furthermore, four additional requirements are prescribed for the Askarel insulated transformer rooms, which include (1) the installation of oil containment, (2) keeping the room free of combustibles, (3) properly seal the wall penetrations and (4) exhausting air directly to the outside.

Electricity provider (1):

This organisation is one of the largest electricity network management companies in the South Island of New Zealand. The fire protection requirements for distribution substations are found in one of their electricity network design standards produced in 2001. This guideline recommended distribution substations to be located at ground level with at least one wall is an external wall. When liquid type transformers are used in the building, it shall be installed in a vault constructed with a minimum of 2 hour FRR. Any openings and penetrations within the FRR barrier shall be properly sealed or an automatic closing damper shall be provided. Ventilation systems are also recommended. If natural ventilation is used, the combined net area of all ventilating openings shall be not less than 2000mm^2 per kVA of transformer capacity in service (1.5m^2 for a 750kVA transformer). If mechanical ventilation is used, the airflow rate at 40m^3/min per transformer is required.

Electricity provider (2):

This organisation is another electricity network company in New Zealand but their major customers are in the North Island. They created a fire protection guideline for distribution substations in 1997. Their fire protection requirements are based on the Electricity Regulations 1997 and the Building Act 1991. As recommended in this guideline, the fire load density in a distribution substation shall be considered to contain a total of 3500MJ/m^2 with FHC of 4. It is recommended that the distribution substation should be constructed with a minimum of 2 hour FRR or it can be reduced to 1 hour FRR if sprinkler system is installed.

3.8 Comparison of Transformer Fire Protection Requirements

A summary of fire protection requirements for distribution substations in typical residential and commercial mixed-use buildings from the above standards and guidelines is illustrated in Table 3-3 through to Table 3-7:

Table 3-3: Summary of the general fire protection requirements for a distribution substation in a typical residential and commercial mixed-use building

Fire protection requirements	C/AS 1	NZFS	NFPA	BCA	IEEE	FM Global	Electricity provider (1)	Electricity provider (2)
Detection system	Heat/ Smoke detector	Heat detector	Smoke detector	Smoke detector	Heat/ smoke detector	Smoke detectors	Smoke detectors	Not Spec.
Sprinkler system	See tables below	See tables below	See tables below	See tables below	See tables below	See tables below	See tables below	See tables below
FRR construction	See tables below	See tables below	See tables below	See tables below	See tables below	See tables below	See tables below	See tables below
Smoke management system [1]	Not Spec.	Not Spec.	Req.	Not Spec.	Req.	Req.	Req.	Not Spec.
- Natural venting (Venting openings)	N/A	N/A	>1.425 m^2	N/A	Not Spec.	Not Spec.	>1.5 m^2	N/A
- Mechanical venting (Airflow rate)			Not Spec.				>40 m^3/min	
- Auto closing damper			Req.				Req.	
Location of distribution substation (on an external wall)	Not Spec.	Rec.	Rec.	Not Spec.	Not Spec.	Rec.	Rec.	Rec.
Oil containment [2]	Not Spec.	Rec.	Rec.	Not Spec.	Rec.	Rec.	Rec.	Not Spec.

[1] Either natural venting or forced venting is installed

[2] For liquid type transformer only

Where Spec. = specified; Req. = required; Rec. = recommended; N/A = Not Applicable

Table 3-4: Summary of the specific fire protection requirements for flammable liquid insulated transformers in a distribution substation

Specific requirements for flammable liquid insulated transformers [1]	**C/AS 1**	**NZFS**	**NFPA**	**BCA**	**IEEE**	**FM Global**	**Electricity provider (1)**	**Electricity provider (2)**
Option 1: Provide FRR construction and no sprinkler system								
FRR construction	1 hour	4 hour	3 hour	Not Spec.	Not Spec.	3 hour	2 hour	2 hour
Option 2: Allow the reduction to FRR construction by providing sprinkler system								
FRR construction	Not Spec.	Not Spec.	1 hour	2 hour	Not Spec.	1 hour	Not Spec.	1 hour
Sprinkler system (Discharge density)			Req. (10.2 mm/min)	Req. (Not Spec.)		Req. (15 mm/min)		Req. (Not Spec.)

[1] Two alternative fire safety designs to meet the standards and guidelines when a flammable liquid insulated transformer is installed.

Table 3-5: Summary of the specific fire protection requirements for less flammable liquid insulated transformers in a distribution substation

Specific requirement for less flammable liquid insulated transformers [2]	**C/AS 1**	**NZFS**	**NFPA**	**BCA**	**IEEE**	**FM Global**	**Electricity provider (1)**	**Electricity provider (2)**
Option 1: Provide FRR construction and no sprinkler system								
FRR construction	Not Spec.	Not Spec.	3 hour	Not Spec.	Not Spec.	1 hour	Not Spec.	Not Spec.
Option 2: Allow the reduction to FRR construction by providing sprinkler system								
FRR construction	Not Spec.	Not Spec.	1 hour	Not Spec.	Not Spec.	No FRR req.	Not Spec.	Not Spec.
Sprinkler system (Discharge density)			Req. (Not spec.)			Req. (10 mm/min)		

[2] Two alternative fire safety designs to meet the standards and guidelines when a less flammable liquid insulated transformer is installed.

Where Spec. = specified; Req. = required;

Table 3-6: Summary of the specific fire protection requirements for Askarel/ non-flammable liquid insulated transformer in a distribution substation

Specific requirement for Askarel/ non-flammable liquid insulated transformers	C/AS 1	NZFS	NFPA	BCA	IEEE	FM Global	Electricity provider (1)	Electricity provider (2)
FRR construction	Not Spec.	Not Spec.	No FRR req.	Not Spec.	Not Spec.	No FRR req.	Not Spec.	Not Spec.

Table 3-7: Summary of the specific fire protection requirements for dry type transformer in a distribution substation

Specific requirement for dry type transformers	C/AS 1	NZFS	NFPA	BCA	IEEE	FM Global	Electricity provider (1)	Electricity provider (2)
FRR construction	Not Spec.	Not Spec.	1 hour	Not Spec.	Not Spec.	No FRR req.	Not Spec.	Not Spec.

Where Spec. = specified; Req. = required;

CHAPTER 4 REVIEW OF TRANSFORMER FIRE

4.1 Introduction

In this chapter, several literature sources have been reviewed in relation to transformer fires, the health effect of a transformer fire, the fire resistance rating of construction, evacuation from high rise buildings during a fire, characteristics of transformer fires and the properties of the major combustible material in transformer i.e. dielectric material. Other informative studies, such as transformer ageing and cost comparison between different types of transformer are also reviewed to provide background information for the cost benefit assessment.

This chapter does not provide the literature review on the specific factors and parameters used in the risk assessment i.e. event tree analysis and cost-benefit analysis. These reviews are to be provided in the relevant sections in Chapter 7 and Chapter 8.

4.2 Fire Resistance Rating of Construction

At the Building and Research Association of New Zealand (BRANZ), the fire resistance time of building elements is commonly determined by the ASTM or NFPA fire endurance test using the standard ISO fire curve as described in Australia standard AS1530.4-2005, which is similar to ISO 834 or British Standard BS 476 part 20-22 and ASTM E119, to provide a fire rating. However, research has been performed to study the behaviour of structures in the case of ISO fire exposure and a real fire exposure. It is found that the actual fire resistance time of building elements exposed to real fire conditions could have significantly different times from the fire rating derived from standard tests, depending on the characteristics of real fire, such as fire growth rate, fire load density, location of fire, and the geometry of the fire compartment, such as compartment size, ventilation conditions, opening definition, glass breaking.

Nyman [43] has recently studied the equivalent FRR of construction elements exposed to realistic fires. In the research, three full-scale compartment tests were experienced, establishing the actual times to failure of construction with real fire exposure, and compared the results with the fire resistance rating of the construction derived from standard tests. The outcome of the research shows that standard fire test method with ISO fire curve is considered not conservative for use on load-bearing building elements. It has found that real fire exposure can be more severe than the AS1530.4 standard furnace test exposure. It can grow quicker than standard ISO fire, increase the compartment temperature in the fire growth phase and cause the failure of building elements, such as integrity, insulation and stability, to occur earlier than the fire resistance rating. In the conclusion, it stated that the failure times of the test assemblies in the compartment tests confirms that construction exposed to realistic fires will fail at times significantly less than the FRR derived from standard tests, for fires which are more severe than the standard test fire exposure.

A fire curve for Hydrocarbon heating regime, which has a more rapid fire growth in the earlier stage, is introduced in the AS1530.4-2005 standard for measuring the FRR. This fire curve can predict the FRR construction in a more severe fire environment. However, since the use of alternative heating regime is optional in accordance with Appendix B of the AS1530.4-2005 standard, fire curve for Hydrocarbon heating regime is not commonly used.

4.3 Evacuation in High Rise Building

In a high rise building occupied with residential and commercial space, the evacuation time of the occupants could potentially take more than couple hours to evacuate the building. Technically, the required safe egress time (RSET) is defined as the time required for evacuation of occupants to a place of safety. As stated in the fire engineering design guide [32], the RSET can be determined by sum of fire detection time, pre-movement time, travel time and queue time. In residential buildings, occupants may or may not be alert, awake and familiar with the building fit-out and the location of exits (e.g. new tenants or guests). As the result, the RSET of these buildings could potentially be very long. Several studies have conducted a great deal of research into human behaviour and evacuation in high rise apartment (residential) buildings. The major findings are summarized as follows:

- Proulx [44] & [45]: The pre-movement time in an actual apartment (residential) building fire are found to be in a range of 0.5 minutes with good alarm and 192 minutes with no alarm (more than 3 hours), depending on the following factors:

    - Alarm type and audibility.
    - Visual access
    - Responsibility for others
    - Training
    - Weather

  In Proulx's studies, some occupants did not evacuate i.e. chose not to evacuate and waited for fire brigade.

- Brennan [46]: The pre-movement time in a night time apartment (residential) building fire is in a range of 0.5 – 20 minutes. However, almost half of the building occupants did not evacuate for first few hours; i.e. did not know (are not alert or awake), did not respond to door knocking, or chose not to evacuate.

- VUT [47]: 50% of occupants in a residential building did not evacuate for first few hours in a case of a real fire.

- SFPE [48] stated that "*Alertness and limitation: A fire in the middle of the night in a hotel or residential building will require a longer time to respond since most occupants will be asleep. Another dimension to this characteristic is the possibility that occupants may have some limitation that will extend their response time. These limitations could be perceptual, physical, or intellectual, or might be due to the consumption of medication, drugs, or alcohol. It is important to estimate the proportion of occupants who will have a longer delay time to start due to alertness conditions or a limitation.*" In addition, the SFPE also stated that if the building often has false alarms, it could be expected that the delay time to start will be extensively extended since building occupants are unlikely to look for information and will be less receptive to other cues.

From the literature, it is understood that, in the worst case scenario, occupant evacuation in a high-rise building could potentially take up to several hours to the outside of the building due to poor alarm notification, lack of training, frequency of false alarms, alertness and limitation, unfamiliarity with the building fit-out.

4.4 Study on the Health Effect of Exposure to A Transformer Fire

4.4.1 Fitzgerald et al. (1981)

The American medical association, and the American Academy of occupational medicine and society for occupational and environmental health studied the health effects to patients, who were potentially exposed to polychlorinated biphenyls (PCB's), and polychlorinated dibenzo-p-dioxins (PCDF's) from an electrical transformer fire in New York on February, 1981 [49]. The transformer fire occurred in the basement mechanical room of an 18-story structure in the city centre. Approximately 681 litres of Askarel oil (65% PCB's – Aroclor 1254 and 35% polychlorinated benzenes) leaked from a transformer. The toxic gases produced by the transformer were spread throughout the building via the two ventilation shafts.

A health survey was conducted three years after the fire and a total of 479 occupants of the building and firefighters were studied in the research. The survey has achieved an excellent response rate from the participants; almost 80% returned their questionnaire. As the results were analysed, it was found that skin itching (23.7%) was the most commonly reported symptoms after the fire and other symptoms included headaches (22.5%), nervousness or sleep problems (20.3%), rashes or dermatitis (20.1%) and vision changes (17.4%). In addition, several occupants were diagnosed to have an invasive cancer after the fire, which included a thyroid cancer diagnosed in 1982, a lung cancer and a brain tumour diagnosed in 1984.

4.4.2 Eschenroeder & Faeder (1988)

The objective of Eschenroeder and Faeder's study [50] is to estimate the risk of health effects due to the inhalation of combustion products from mineral oil transformer fires using Monte Carlo analysis. This is a means of statistical evaluation of mathematical functions using random samples. In the research, Eschenroeder and Faeder have considered polychlorinated dibenzofurans (PCDF's) from the pyrolysis of polychlorinated biphenyls (PCB's) as the main toxic products that would be produced in an event of accidental fires involving mineral and Askarel mixture oil insulated transformers. The two main findings of the report were the cancer risk and the birth defect (health hazard) associated with a mineral and Askarel mixture oil transformer fire.

As defined in the report "*the definition of risk is based on a chance event derived from model uncertainties rather than physical events*". Therefore, estimation is highly dependant on the existing statistical data. Hence, this report has included the uncertainty study which can provide quantitative measures of health conservatism by assigning confidence levels to different numerical estimates. As a result of the analysis, the health risk from PCB-contaminated mineral oil transformer fire was found to be insignificant both in case of cancer burden and in the case of birth defects. Based on the Monte Carlo results, the probability of the occurrence of a cancer burden of unity and to the health hazard burden of unity was found to be 1.6×10^{-9} and 1.7×10^{-14}, respectively.

4.5 Experiment on Transformer Oil Fire

4.5.1 Heskestad & Dobson (1997)

Heskestad and Dobson [51] reported two experiments on pool fires of transformer oil burning over a rock bed in a 1.2 m diameter pan and the report was published in the Fire Safety Journal 1997. The difference between the two tests was that one had drainage at regression rates of 16 to 26 mm/min from the bottom of the plan and one was without drainage. The simple transformer oil used for the experiments has a flash point of 157ºC (See Section 4.8 for the comparison of the transformer dielectric fluids properties). As the results of the experiments, the peak convective heat release rate from the transformer oil burning was found to be between 750kW and 1MW. The HRR curve from both tests is shown in Figure 4-1 and Figure 4-2.

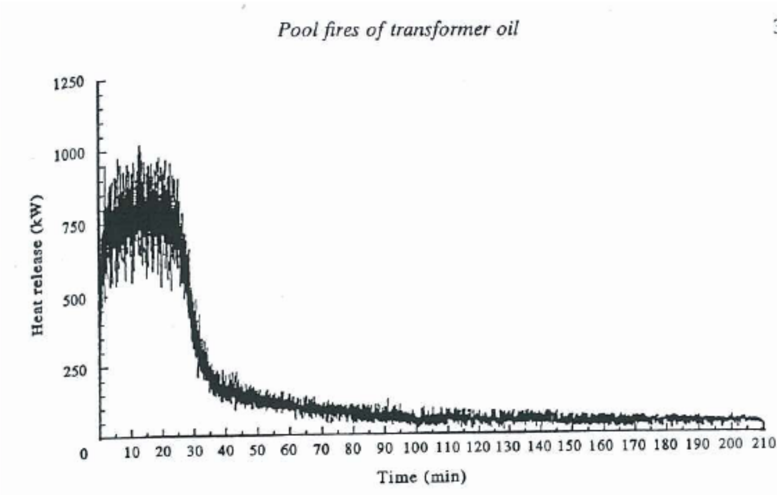


Figure 4-1: Convective HRR of transformer oil with no drainage, extracted from Heskestad & Dobson (1997)

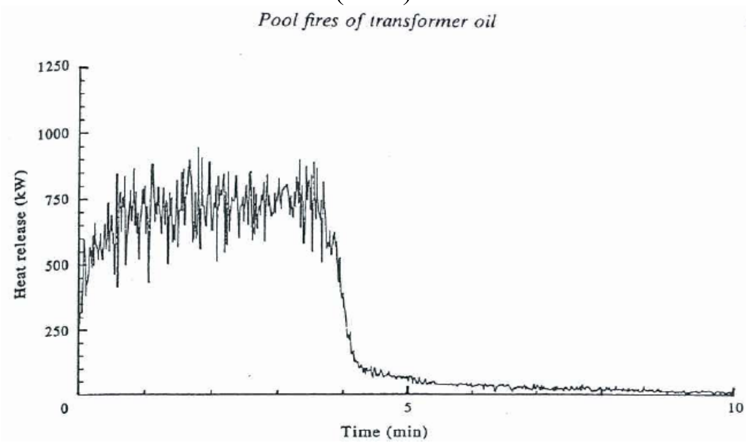


Figure 4-2: Convective HRR of transformer oil with drainage, extracted from Heskestad & Dobson (1997)

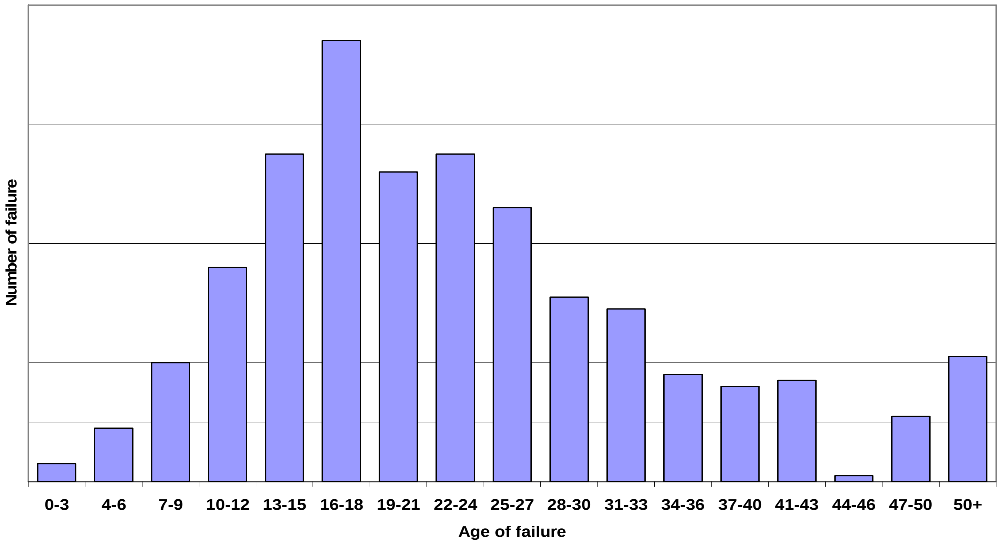
4.6 Transformer Ageing

4.6.1 Bartley (2000, 2002 & 2003)

William H. Bartley has been investigating transformer failure, transformer ageing and transformer life cycle management with Hartford Steam Boiler Inspection & Insurance Co. U.S. since year 2000. Five of the relevant articles are:

- Analysis of Transformer Failures – A Twenty Year Trend, (Bartley 2000 [52])
- Life Cycle Management of Utility Transformer Assets (Bartley 2002 [53])
- Analysis of Transformer Failures (Bartley 2003 [29])
- Investigating Transformer Failures (Bartley 2003 [54])
- Transformer Asset Management (Bartley & James 2003 [55])

Bartley has highlighted that transformer ageing is one of the main issues causing transformer failures. Unlike other common causes of failure, such as failure due to electrical disturbances, insulation issues, maintenance issues, lighting, loose or high resistance connection, overloading and sabotage, transformer failure due to transformer age is very difficult to identify. Based on Bartley's studies, the mean age at failure for utility transformers was found to be 17.7 years as shown in Figure 4-3.



(Note that the number of failures was missing in the original report)

Figure 4-3: Number of transformer failures, reproduced from Bartley 2000 [52]

Further to Bartley's discussion [52], an equation was developed to predict the future transformer failure as follow:

Equation 4-1:
$$f_{(t)} = \frac{\omega + \alpha e^{\beta t}}{1 + \mu e^{\beta t}}$$

where $f_{(t)}$ is the instantaneous failure rate

ω is a constant for random events (0.005)

α is a constant

μ is a constant

β is a time constant

t is time (year)

Based on the data recorded by Hartford Steam Boiler Company, the property damage due to transformer failure and fire, excluding business interruption losses, was found to be approximately USD$9 per kVA in an average five years period. This extrapolates to USD$6,750 for a 750kVA transformer.

4.7 Cost Effective Comparison between Different Types of Transformers

4.7.1 Goudie & Chatterton (2002)

Goudie and Chatterton [56] reported a comparison between the use of dry (solid or gas) type and liquid type transformers in distribution substations at the standpoint of economics and the environment with regards to the transformer lifetime. This report also compared the common transformer dielectric fluids in terms of the economic, environmental and life safety factors.

Overall, the report concluded that the use of liquid type transformers would have more benefit than dry type transformers and the main discussions are summarised as follow:

- Liquid type transformers are more efficient then a dry type transformer; in other words, the energy loss by using a dry type transformer is much higher than a liquid type transformer
- Less carbon dioxide would be produced by using liquid type transformers
- Dry type transformers may require higher maintenance cost due to periodic cleaning since the coils are open to dust and pests.
- Typically, dry type transformers are physically larger than liquid types and, hence, larger cores may be required that would lead to have a higher iron or core loss.

Furthermore, the report also provided an initial cost relationship of transformer. It used the cost of a mineral oil filled transformer as a base point and measure the relative initial cost for other type of transformers. The table is extracted from the original article and shown in the following figure:

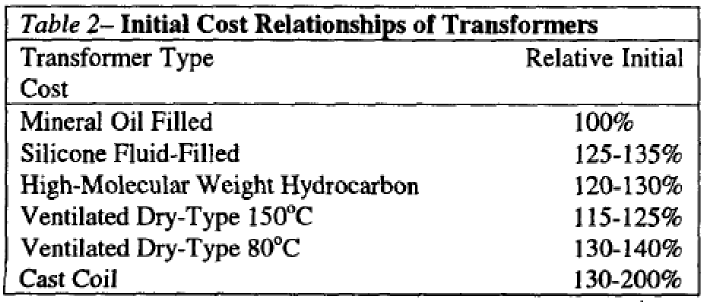


Table 2– **Initial Cost Relationships of Transformers**

Transformer Type	Relative Initial Cost
Mineral Oil Filled	100%
Silicone Fluid-Filled	125-135%
High-Molecular Weight Hydrocarbon	120-130%
Ventilated Dry-Type 150°C	115-125%
Ventilated Dry-Type 80°C	130-140%
Cast Coil	130-200%

Figure 4-4: Initial cost for transformer dielectric materials, reproduced from Goudie & Chatterton (2000)

4.8 Studies on the Dielectric Fluids

The properties of transformer dielectric fluid have been summarised in the table below from the relevant literature. These literature include Oommen [19], Mcshane [21], Goudie and Chatterton [56], Babrauskas [57], Bertrand [58], ASTM D4652-92 [59], ASTM D3487-00 [60], ASTM D2283-86 [61], Trabulus [62] and Patel [63].

Table 4-1: Properties of transformer dielectric fluid: Typical Values/ Limits

Properties		Units	Mineral Oil	Silicone Oil	Vegetable Oil	Askarels
Dielectric Breakdown		kV	30 - 85	35 - 60	82 - 97	35
Relative Permittivity at 25°C			2.1 - 2.5	2.6 - 2.9	3.1 - 3.3	3.7 - 4.9
Viscosity	0 °C	mm^2.s^{-1}	<76	81 - 92	43 - 77	Not stated
	40 °C	mm^2.s^{-1}	3 - 16	35 - 40	16 - 37	31 - 92
	100 °C	mm^2.s^{-1}	2 - 3	15 - 17	4 - 8	Not stated
Pour Point		°C	-30 - -60	-50 - -60	-19 - -33	-14 - -44
Flash Point (open cup test)		°C	100 - 170	300 - 310	310 - 328	None to boiling
Fire Point (open cup test)		°C	110 - 185	340 - 350	350 - 360	None to boiling
Density at 20°C (specific gravity)		kg.m^{-3}	830 - 890	960 - 1100	870 - 920	1380 - 1570
Specific Heat capacity		kJ.kg^{-1}K^{-1}	1.6 - 2.39	1.5 - 2.04	1.5 - 2.1	Not stated
Thermal Conductivity		W.m^{-1} K^{-1}	0.11 - 0.16	0.15	0.16 - 0.17	Not stated
Expansion Coefficient		10^{-4}.K^{-1}	7 - 9	10 - 10.4	5.5 - 5.9	7
Heat of combustion		MJ.kg^{-1}	45.9	28	35	Not stated
Moisture content, dry oil		ppm	10 - 25	50	50 - 100	30
Volume resistivity at 25°C		Ω.cm	10^{14} - 10^{15}	10^{14}	10^{14}	10^{11}
Interfacial tension at 25°C		dynes/cm	40 – 45	25	25	Not stated
Heat release rate [1]		kW/m^2	>1000 (1538 - 1625)	< 1000	Note stated	Not stated

[1] Typical HRR for mineral oil is found as indicated in the bracket

CHAPTER 5 DATA COLLECTION

5.1 Statistical Studies

5.1.1 Sources of Data

The statistical data given in this section is based on three databases: (1) the annual statistics from the Ministry of Commerce in New Zealand, (2) the fire incidents statistical data from the Fire Incident Reporting System (FIRS) managed by the New Zealand Fire Service (NZFS) and (3) the fire incidents statistical data from the National Fire Incident Reporting System (NFIRS) managed by the National Fire Protection Association (NFPA).

The Ministry of Commerce, now known as the Ministry of Economic Development (MED), is a government department responsible for the government ownership of public properties. The number of distribution substations and the population in New Zealand are provided in their annual statistics reports (Refer to Section 5.1.3). It was found that the population in New Zealand is increasing with an average growth rate of 1.5% per year over the past 50 years. This information implies that increasing number of high-rise buildings is required due to the growing population in New Zealand. As a result, distribution substations are expected to become more commonly built in buildings due to the higher loading density. The statistical data on the number of distribution substations in New Zealand was obtained from the MED between 1946 and 1995. Since the statistical data after 1995 was not available, the number of distribution substations between 1995 and 2006 is estimated based on the growth rate measured in the previous 50 years.

The purpose of the FIRS system is to collect and analyse data on fire incidents from the Fire Services throughout New Zealand. Generally, the fire incidents can be classified mainly in terms of their property types, location of fire origin, item first ignited and heat source. According to the NZFS FIRS instruction and coding manual [64], the specific property use of

"6401- substations, transformers and power lines" is found under Code 64: Utilities and Energy distribution. As the location of fire origin, the switchgear areas and transformer vaults are found in Code 173. Based on these two criteria, 24 fire incidents were selected from the NZFS FIRS database during the 6 years period from January 2000 to January 2006 [65]. Out of the 24 fire incidents, 20 fire incidents are related to distribution substations and 4 fire incidents are related to power or terminal substation. It is noted that the statistical data from the NZFS FIRS provided only the significant information to the fire incidents, such as the incident time frame, the incident type, the fire cause and the consequence. No specific information was recorded in these incident reports, such as the characteristic of the properties, the number of fatalities and the cost of property damages. Therefore, the consequence of structure fires originating in switchgear areas or transformer vaults reported to the NFIRS [66] is also examined in this research for reference.

5.1.2 Historical Case Study for Transformer Fires

Two critical distribution substation fire incidents reported between 2000 and 2006 in New Zealand are discussed in this section. These fire incidents were all involved with transformer fluid. Since no further investigation reports were found, the discussions are based on the incident reports provided by the NZFS. These reports briefly record information about the fire and the message log during the incident; however, the consequence of these fires was not clearly stated. Due to the low number of transformer fire incidents occurred in New Zealand, three additional transformer fire incidents in U.S. are discussed in this section for reference.

On the 24th January 2002, a distribution transformer in Napier caught fire. The heat source was estimated to be electrical arcing and the first ignited material was transformer fluid. Of the 20 fire incidents involving distribution substations, this incident was the only one that mentioned the performance of the detection system. According to the incident report, a smoke detector was installed in the building and was monitored. However, although the detector was installed so it operated in an event of fire, it was not a factor in discovery of this fire. In this case, the Fire Service was alerted by an emergency call 111 from an occupant. No information about casualties and property damages was found in the incident report.

On the 21st June, 2003, an 11kV/415V step-down transformer was totally involved during a fire in Christchurch. It is different to the previous incident as the ignition source in this case was arcing from a faulty, loose or broken conductor and the first ignited object was the electrical wire and wiring insulation, followed by the transformer fluid. When the Fire Service arrived at the scene, the fire was already fully developed in the distribution substation. Therefore, the firefighters decided to take no action until the power for the whole street was turned off as it was extremely dangerous. Later, the fire was confined to the structure of origin. As a result of the fire, the structure was badly damaged but no injuries were recorded.

In the morning of 24th July, 1984, a transformer fire occurred at the New York University Medical Centre and was followed by an explosion. As Ragusa [67] stated, there were a total of four transformers on the site. These transformers were 13.8kV/ 460V step-down transformers. Mineral oil was used as the cooling medium and the units were installed in a distribution substation. The cause of the fire was believed to be that the unit was overheated and ignited the leaked transformer oil. There were no injuries in the event. Damage to the equipment was not given in this article.

Another distribution transformer fire was discussed by Courtney [68]. The transformer fire occurred in 1988 when the power was restored after a shut down for repairs. The fire ignition source is believed to have been electric arcing inside the oil insulated transformer. As a result of this transformer fire there were a total of four casualties; one minor and three serious injuries, and property damage of USD$23,000 (1988).

A distribution transformer caught fire in a hospital in 1996 as Tremblay [69] stated. The hospital is a three storey building with FRR construction, however the nature of the fire rated construction was not recorded. Smoke detection systems and sprinkler systems were installed throughout the building. The transformer fire was detected by the detection systems soon after the fire started and was successfully extinguished by the sprinkler systems, which was activated by the Fire Service. The cause of the fire was that the unit was overheated and ignited the leaked transformer oil. Due to the early occupant warning alarm, there were no injuries as a result of this transformer fire. The fire was confined to the room of origin and property damage was estimated to be USD$10,000 (1996).

5.1.3 Number of Distribution Substations in New Zealand

According to the data from the MED database: the New Zealand Energy and Resources Division and Market Information and Analysis Group [70], the New Zealand Energy Modelling and Statistics Unit [71] and [72], and the New Zealand Ministry of Energy [73], the number of distribution substations in New Zealand increased from a total of 24,000 in year 1946 to 140,000 in 1995 as shown in Figure 5-1. These distribution substations might contain a single or multiple transformer(s) with a voltage rating of 11kV or less. Based on the available data, the growth rate is estimated to be 1.71% per annum as the solid line shown in Figure 5-1. Following the estimated growth rate, the number of distribution substations in 2006 is determined to be 167,000. The data is listed in Appendix C.

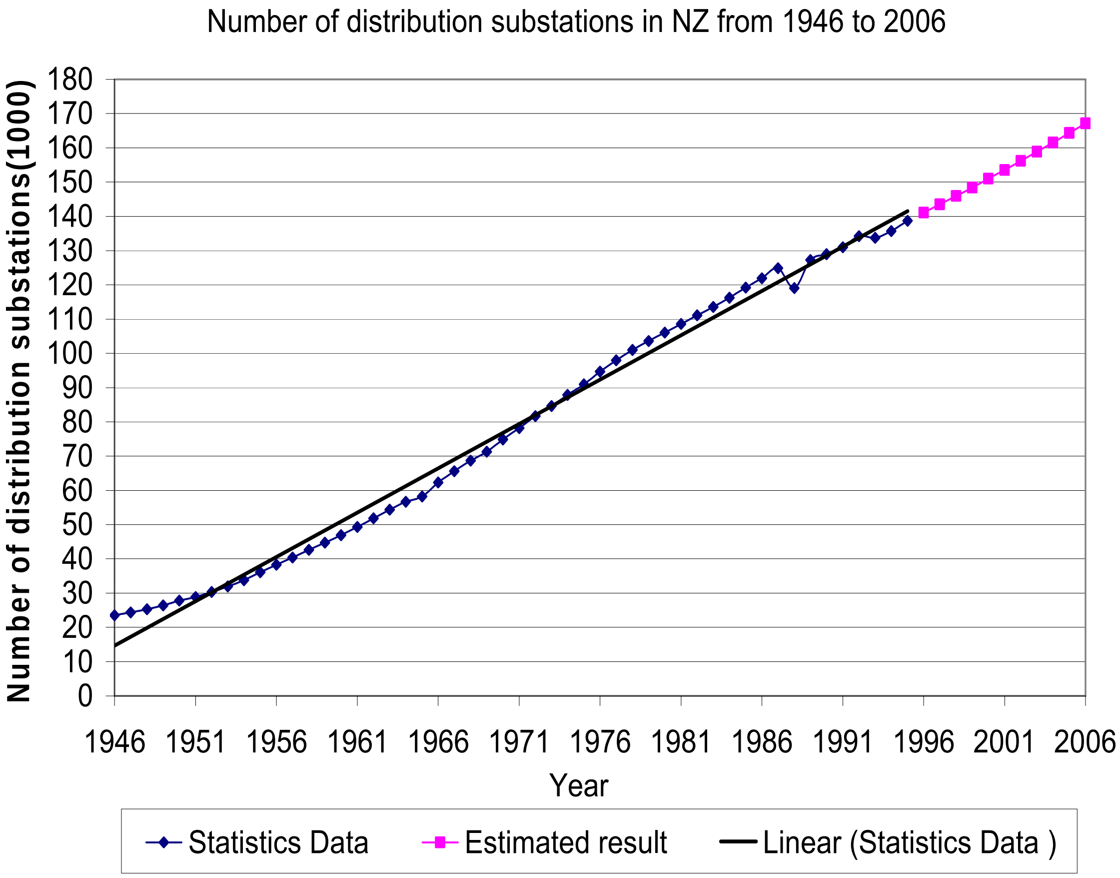


Figure 5-1: Number of distribution substations in New Zealand from 1946 to 2006

5.1.4 Fire Incidents Reported to the NZFS FIRS

Each year between 2000 and 2006, an estimated 4 fire incidents were reported to the NZFS FIRS in relation to the specific property use of substation and the fires originating in switchgear areas or transformer vaults as shown in Figure 5-2. Of the 24 fire incidents during the 6 year period, 20 involved indoor transformers. With these fires, only one injury was reported to the NZFS FIRS. In addition, the property losses associated with the fire incidents could not be found from these incident reports. The statistical data addressed in this section include:

- Number of distribution substation fires
- Monthly trends
- Time of day
- Equipment involved
- Source of ignition
- Primary ignition object
- Indicated cause
- Avenue of flame/ smoke travel and their extent damage

Note that the statistical data of the above phases are attached in Appendix C.

Number of distribution substation fires:

There are a total of 20 fires originating in distribution substations reported to the NZFS FIRS during the 6 year period between 2000 and 2006 with a peak of five incidents in the year 2002/03. The best year is found to be the year 2001/02. No fires originating in distribution substations were reported in this period. An average of three to four fire incidents in distribution substations is determined based on the data.

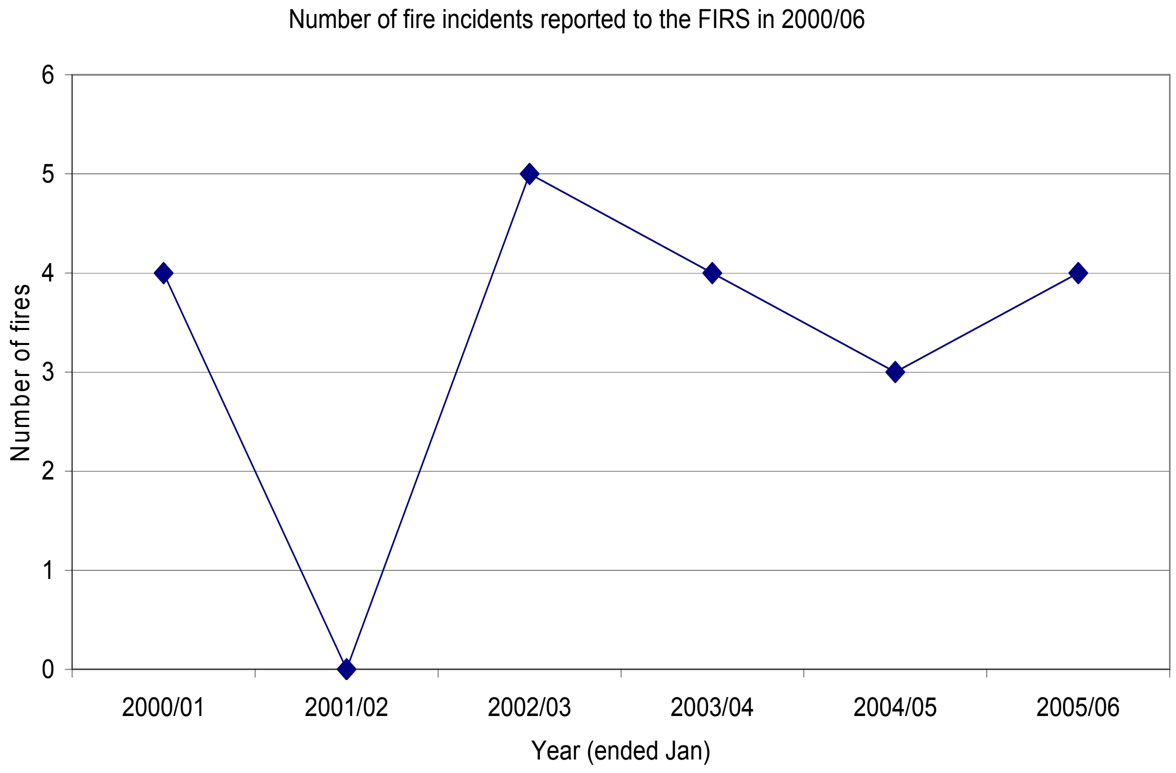


Figure 5-2: Number of distribution substation fires in 2000/06 (Source NZFS FIRS)

Monthly trends

As illustrated in Figure 5-3, the majority of such fires occurred between June and August with a peak in the winter month of June. It was followed by the summer season (December - February). The frequency of the fires is less in spring and autumn (March - May and September - November). This result can be explained by the power consumption. In general buildings, heating and air-conditioning equipment, such as heaters, are often the largest power consumers. As the power consumption increases, the probability of overloading will also increase. According to Hattangadi [28], even though overloading may not directly cause the failure, it may reduce the equipments useful lifetime (Refer to Section 5.2). Specifically, it may be dangerous when overloading equipment that has been in service for more than 30 years. The accuracy of the analysis could be improved when more data is available.

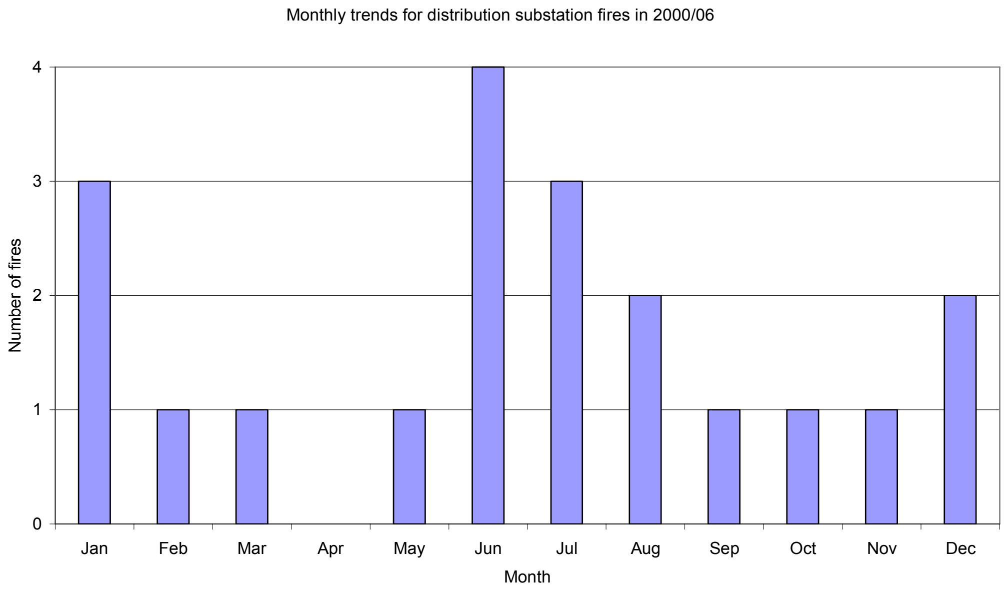


Figure 5-3: Monthly incidence of distribution substation fires in 2000/06 (Source NZFS FIRS)

Time of day

Figure 5-4 shows the hourly trends for distribution substation fires in the period between 2000 and 2006. Typically, these fires are equally distributed into six periods of time. As can be seen, these fires are most likely to occur during ‘work’ hours; between 7am and 3pm, as 9 out of 20 fire incidents occur during these times. It may be again due to higher power consumption during the day than at night.

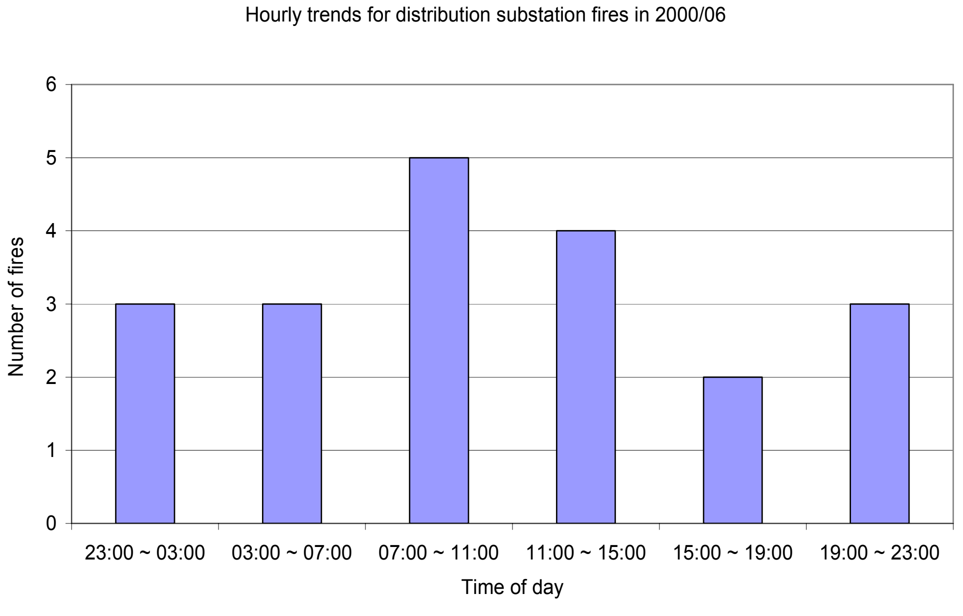


Figure 5-4: Hourly trends for distribution substation fires in 2000/06 (Source NZFS FIRS)

Supposed Causes

According to the NZFS FIRS data, the supposed cause of distribution substation fires can be classified into five groups: (1) Electrical failure, (2) Mechanical failure, (3) Equipment overload, (4) Lack of maintenance and (5) Unknown causes. Figure 5-5 illustrates the leading causes of these fires. The dominant causes are electrical failure (60%); of which 20% were due to short circuits or earth faults and 40% from other electrical failure. The second leading cause of these fires is equipment being overloaded (20%).

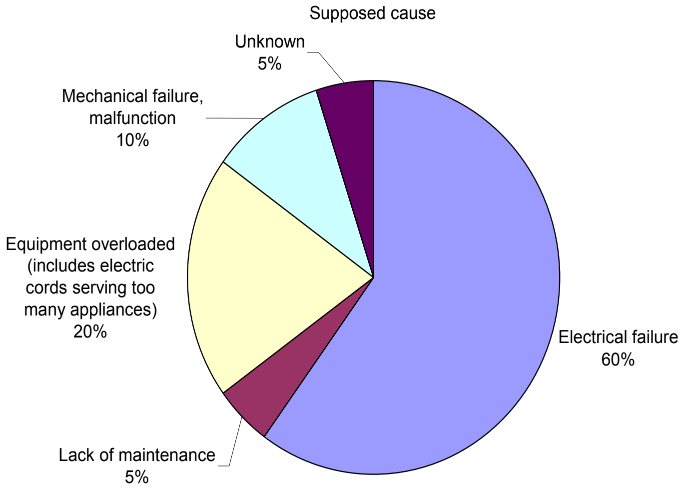


Figure 5-5: Causes of distribution substation fires (Source NZFS FIRS)

Primary ignition object

Generally, the combustible materials in distribution substations may include the electrical wire or cable insulation, transformer (e.g. transformer fluids) and other known items (e.g. wood board and chairs). As a result of the data analysis, 65% of these fires had the electrical wire or cable insulation as the object first ignited (Figure 5-6). Compared to the cable insulation, the probability of having transformer or transformer fluid as the object fist ignited is much lower (20%); however, the consequence of transformer fluid fire could be worse.

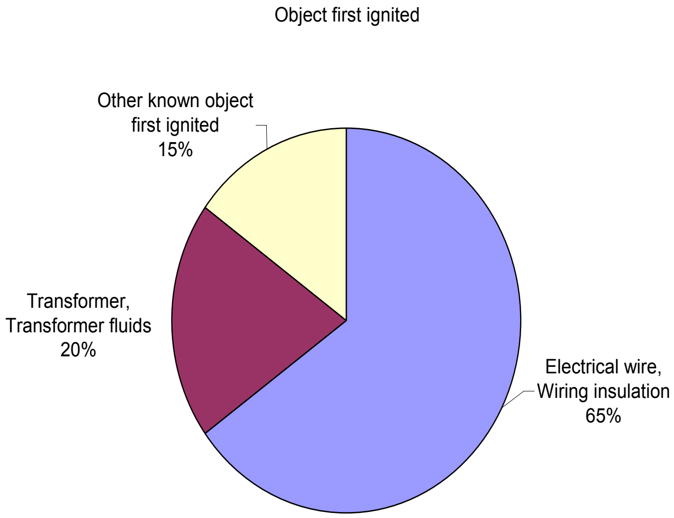


Figure 5-6: Object first ignited (Source NZFS FIRS)

Equipment involved

According to the NZFS FIRS instruction and coding manual [64], the term of equipment involved represents "the equipment that provided the heat for the fire to start, or was involved in the release of hazardous substances". It may sometimes be very difficult to define the equipment involved in some incidents. Out of the 20 fires, there were 6 fires where the equipment involved was not recorded (30%). For the known equipment, there were 7 fires (35%) involving transformer and associated equipment with distribution type recorded. It is followed by the circuit breakers associated with transformers (20%) as the leading type of equipment involved. Other known equipment include the power cables, controlling switches and other not classified items (15%).

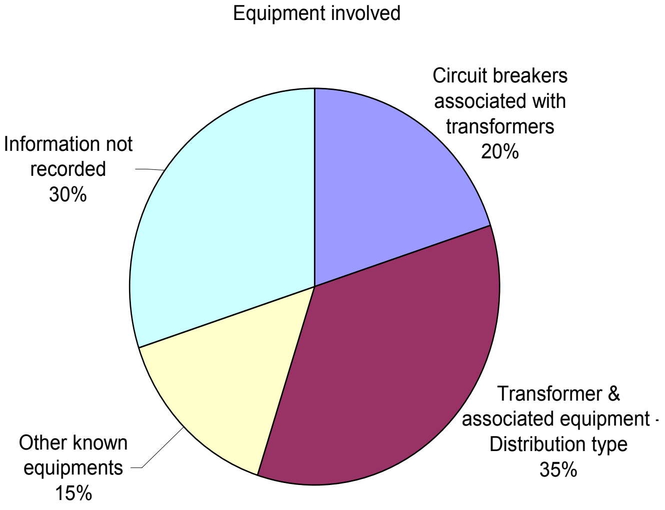


Figure 5-7: Equipment involved (Source NZFS FIRS)

Source of ignition (Heat source)

As the source of heat causing ignition, 70% of these fires involve arcing, either from the short circuit (60%) or from another faulty, loose or broken conductor (10%). Out of the 60% of fires that involved short circuit arcing as the heat source, 5% were caused by water, 10% were from the defective or worn insulation and 45% were unspecified. There are 10% of these fires that have the source heat recorded as overloaded equipment.

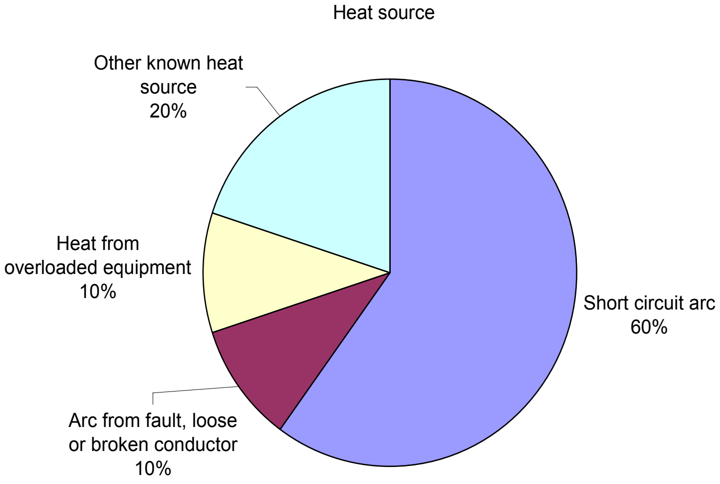


Figure 5-8: Source of ignition (Source NZFS FIRS)

Extent flame/ smoke damage

Figure 5-9 illustrates the extent of flame and smoke damage for the 20 fire incidents analysed. As can be seen in the figure, there are only 12 fires reported to the NZFS FIRS that report the extent of damage. For the extent of flame damage, five incidents were confined to the object of origin and six incidents were confined to the structure of origin. Out of these 6 fires confined to the structure of origin, four incidents involved a transformer, with the transformer fluid as the ignition object. This information supports the concept of having transformer fluid involved in the ignition of a fire being a low occurrence and high consequence event. The avenue of flame travel includes the flammable liquid (2 fires), furniture and fixtures (1fire) or structural member allowing vertical (1 fire) or horizontal travel (1 fire), such as a wall burned through, inadequate fire stopping, air handling ducts, service/pipe shaft or failure of rated assembly. Smoke may not cause any damage if the fire is small enough and the smoke is well controlled by the ventilation system. Similar to flame damage, the fires confined to the structure of origin often had transformer fluid involved as the object ignited.

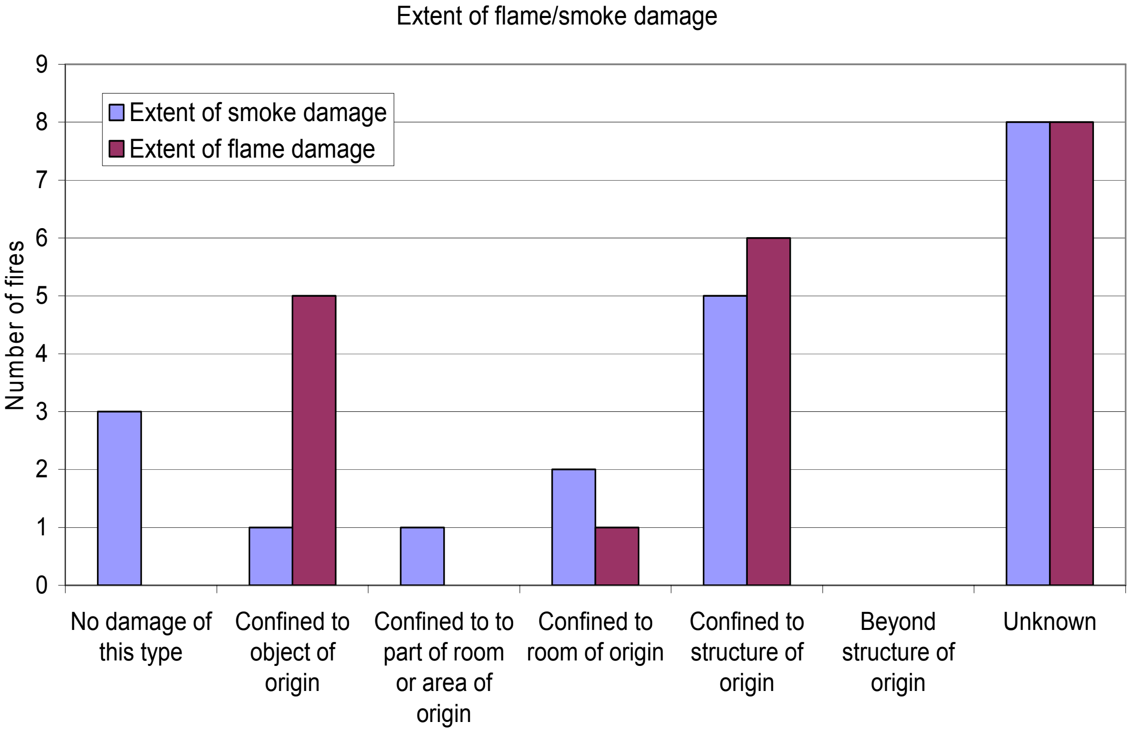


Figure 5-9: Extent of flame/ smoke damage (Source NZFS FIRS)

5.1.5 Fire Incident Reported to the NFIRS (U.S.)

Number of structure fires originating in switchgear areas or transformer vaults

Figure 5-10 illustrates the number of structure fires originating in switchgear areas or transformer vaults during the 22 years period between 1980 and 2002 [66]. As can be seen, there are a total 1890 structure fires originating in distribution substation recorded by the NFIRS in 1980. Since then, the number of fires is decreasing every year with an average decline rate of 55 fires per year as shown by the solid line in Figure 5-10. Until recently in 2002, the number of fires reduced to 680 fires.

Boykin [74] states that the total number of transformers in the U.S. is found to be 23.1 million in 1982. Using the same growth rate of 1.71% per annum as determined in Section 5.1.3, the number of transformers in the U.S. is estimated to increase to about 30 million in 2006.

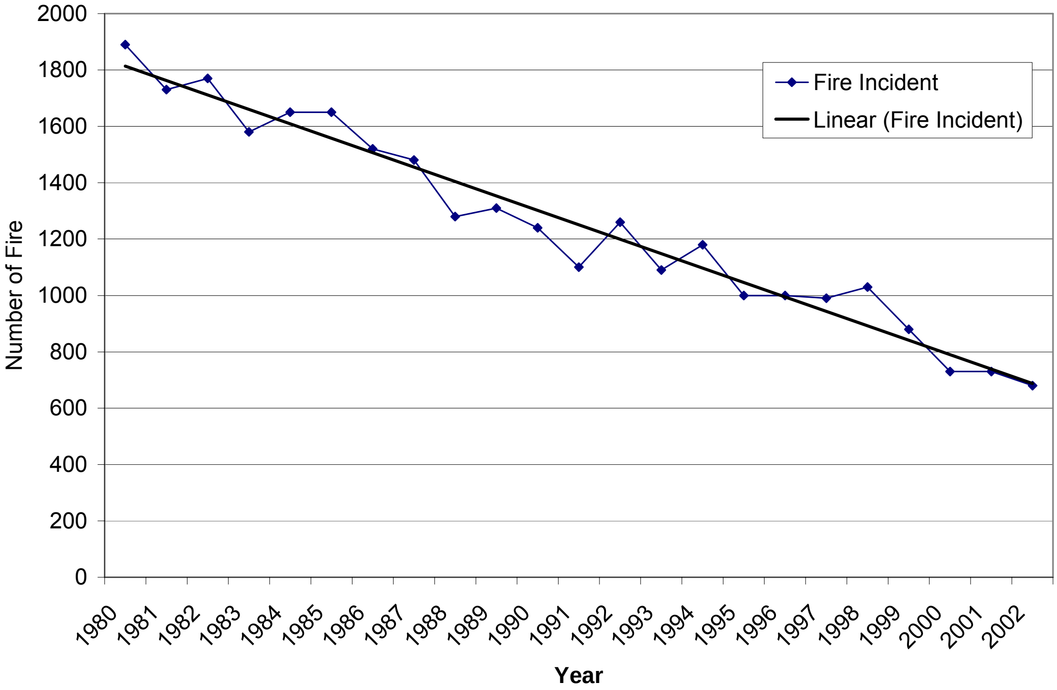


Figure 5-10: Number of structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 (Source NFIRS)

Life safety consequence

The life safety consequence is categorised into two types in the NFIRS data: civilian injuries and civilian deaths. Figure 5-11 and Figure 5-12 illustrate the number of civilian injuries and civilian deaths, respectively, of the structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 in U.S. The data is also attached in Appendix C. While the number of fires is decreasing every year as shown in Figure 5-10, the number of civilian injuries also decreased from an average of 88 injuries before 1995 to an average of 33 injuries after 1996 as shown in Table 5-1. Moreover, although the average number of injuries per fire decreased from 0.06 to 0.04, the number of deaths per fire increased from 0.002 to 0.003 after 1996.

Table 5-1: Life safety consequence of distribution substation fires between 1980 and 2002 reported to the NFIRS

Year	Number of fires	Civilian deaths	Deaths per fire	Civilian Injuries	Injuries per fire
Before 1995 (per year)	1421	3	0.00194	88	0.06177
After 1996 (per year)	863	2	0.00281	33	0.03874
Overall (per year)	1251	3	0.00212	71	0.05693

In regards to life safety, 1999 and 2002 were found to be the worst and the best year respectively, out of the 22 year period. There were a total of 41 civilian injuries and 6 civilian deaths in 880 fires in 1999 and a total of 18 injuries and no deaths in 680 fires in 2002.

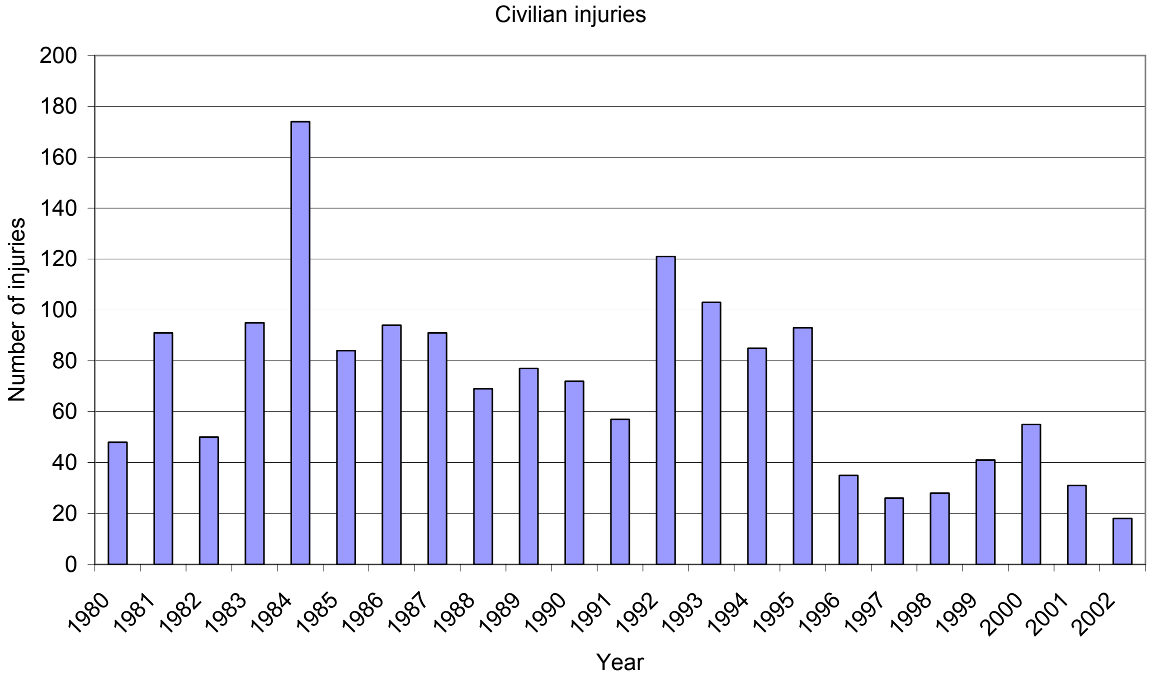


Figure 5-11: Civilian injuries as a result of structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 (Source NFIRS)

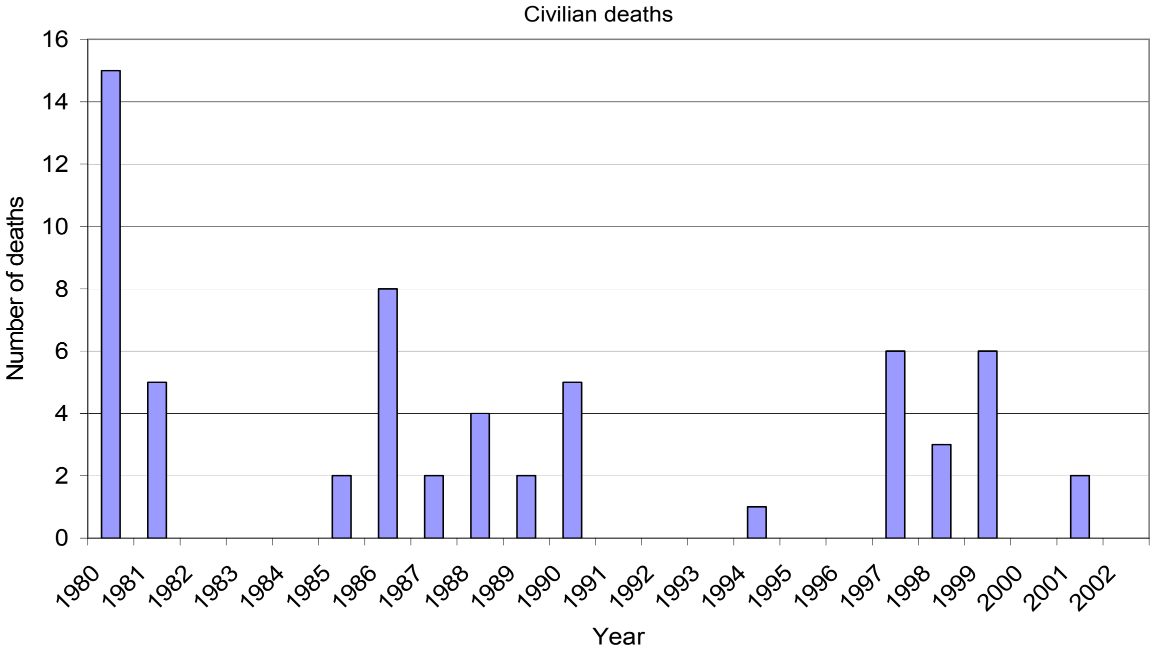


Figure 5-12: Civilian deaths as a result of structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 (Source NFIRS)

Property damage

For the structure fires originating in switchgear areas or transformer vaults reported to the NFIRS between 1980 and 2002, the average property loss is determined to be NZD$50.5 million per year and NZD$40,400 per fire. Note that the costs given in the original data [66] is in USD$ and are converted to NZD$ using the average currency exchange rate of 1.54 [75]. Figure 5-13 illustrates the direct property damage of these structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 in the U.S. in terms of the total property damage costs per year (bar chat), as well as the cost per fire in each year (line curve). The data of these structure fires is referred in Appendix C.

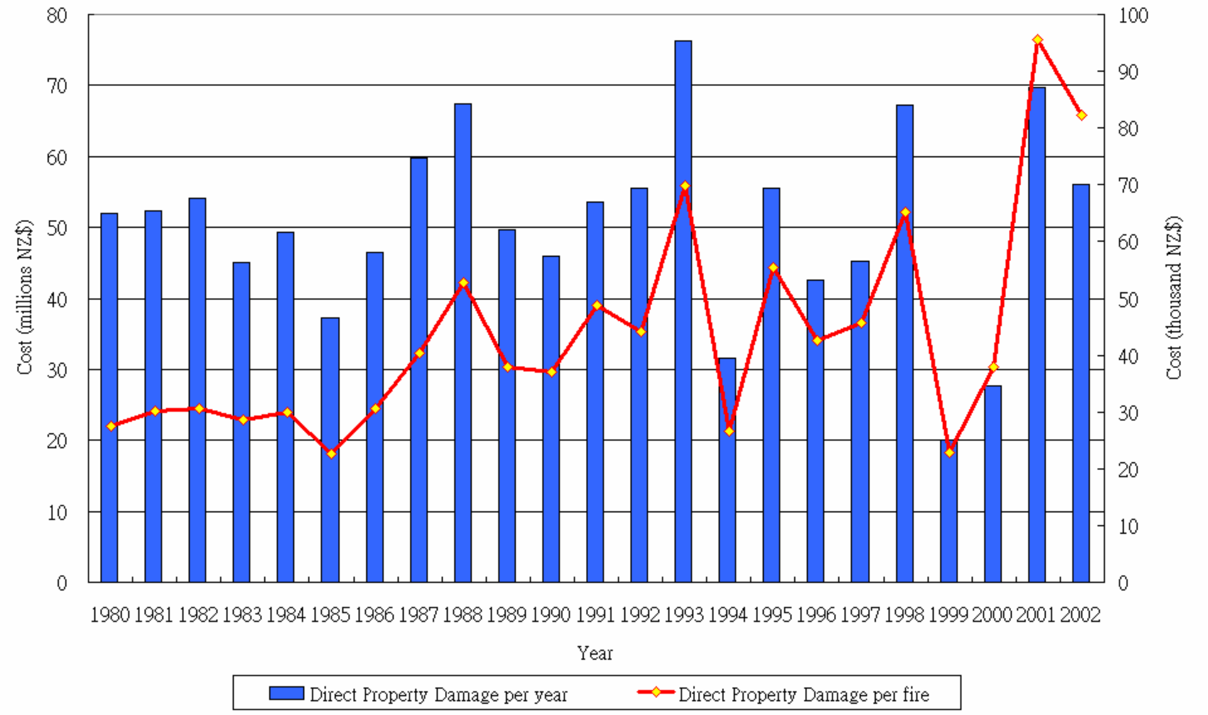


Figure 5-13: Directly property damage as a result of structure fires originating in switchgear areas or transformer vaults between 1980 and 2002 (Source NFIRS)

As can be seen, the largest total direct property damage costs of NZD$76.2 million is found in 1993, while the lowest total costs of NZD$20 million is in 1999. However, when determining the average cost per fire, 2001 is shown to be the worst year and the cost per fire is NZD$95,800. This is due to the relatively low number of fires in 2001 but high property loss from each fire.

5.2 Reliability Data

5.2.1 Transformer and Associated Equipment

Transformers impact distribution system reliability in two related ways: overloads and failures. Transformers may get overloaded from time to time and failures may occur when the transformer is operating with an overload. Overloads may cause the oil temperature to rise up to over the permissible limits, typically 90°C. Hattangadi [28] states that for every 6°C rise in the oil temperature above the permissible limits, the useful life of the transformer is reduced by a period of time which is double the period for which the transformer is operating under the normal temperature. In other words, when a transformer operates with oil temperature of 102°C for one hour, the useful life of the transformer is reduced for approximately four hours. Other potential causes of transformer failure can be found in Section 2.3.4.

From a literature, the typical failure rate of distribution transformers is found to be about 0.02 to 16 failures per 10^6 operation hours as shown in Figure 5-14. This range of transformer failure rate also agrees with the failure rate found from other studies such as Green [76] and the American Institute of Chemical Engineers [77]. Hence, the number of failures per year is determined to be in the range of 180 x 10^{-6} to 140 x 10^{-3} failures per year.

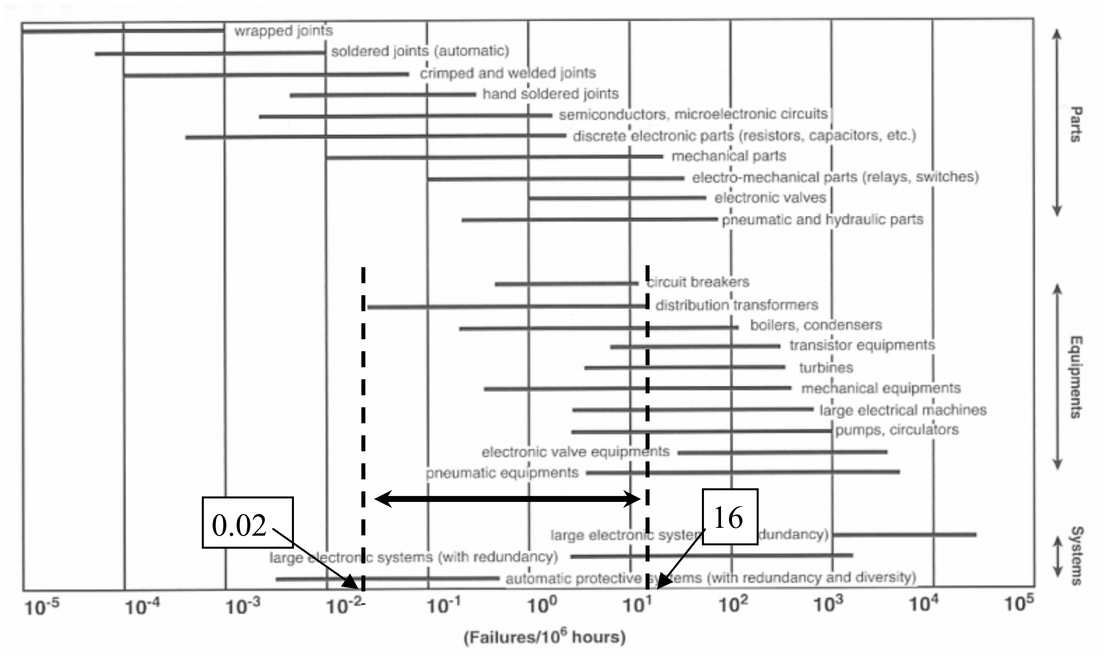


Figure 5-14: Typical failure rates for various equipment (Extracted from Fig. 11.1 of Moss [30])

The failure rates for the distribution transformer and associated equipment, such as the circuit breaker, power cable, capacitor, fuses and the relevant fire protection systems, are obtained from Moss's reliability data handbook [30] as shown in Table 5-2. Failure rate, which is known as a function of time, can generally be defined as the number of failures for a device within a unit of time. As can be seen, the failure rate of the transformer and associated equipment is generally low. The entire transformer systems are always protected and monitored by many protection systems. It is considered that transformer failures may not necessary result in a fire; hence, the probability of transformer fire can be expected to be lower. In addition, the reliability of fire protection systems is relatively low when compared to the transformer and associated equipment. Note that these failure rates are provided solely for information purpose and are not used in the analysis in the report.

Table 5-2: Failure rate for transformer and associated equipment and some fire protection systems

Transformer and associated equipment	Failure per 10^6 hour			Failure / year
	Lower	Mean	upper	Mean
Distribution transformer	0.02	2.53	16	22×10^{-3}
Circuit breaker	0.5	1.03	10	9×10^{-3}
Power cable	0.5	2	2.5	17×10^{-3}
Capacitor	0.0004	0.007	0.075	61×10^{-6}
Fuses	0.0265	0.634	2.36	6×10^{-3}
Fire protection systems				
Fire damper	5	13.7	29.6	120×10^{-3}
Fire fighting system	0.05	36	123	314×10^{-3}
Fire alarm	Not stated	31.9	Not stated	279×10^{-3}
Smoke detection system	6	Not stated	6.7	56×10^{-3}
Sprinkler system	Not stated	0.5	Not stated	4.4×10^{-3}

5.2.2 Fire Protection Systems

Often, the reliability of fire protection systems can be classified into two types, operational and performance reliability. Operational reliability is an estimate of the probability that the system can successfully operate in a fire event. This reliability can be improved with a good maintenance programme. Performance reliability is an estimate of the system adequacy once it has operated. However, as the following reliability data is sourced from various studies, in which the scope, boundaries and breadth may vary significantly, it may not be precise but it could provide an accurate representation of the trend. Note that Table 5-3 and Table 5-4 may consist of studies published in the late 1970's. As expected, standards and codes are improving year-on-year in order to provide equivalent or even higher level of fire safety to the public. In other words, modern fire safety systems are likely to be more reliable and more effective than these fire safety systems maintained using the old standards and codes. Therefore, the analysis including these old data can result a conservative design.

In addition to the reliability of the fire safety systems, the year shown in the tables indicates when these papers were published. Most of these published papers contained the statistical data from a couple years up to a period of 100 years. For system reliability, the more data being studied the better and more comprehensive results that can be obtained. Therefore, these data are considered to be relevant and appropriate for the analysis.

Smoke detection system

As per the prescribed requirements described in Section 1.1, more than half of the standards and guidelines studied have recommended smoke detection systems be installed in the distribution substations in lieu of heat detection systems. Thus, the reliability of smoke detection systems is used for the assessment and, hence, is discussed in this section.

The reliability of smoke detector systems is expressed as the probability that the smoke detector will be activated in the event of a fire. Many researchers have studied the performance of smoke detection system in specific types of buildings or in any buildings in general. However, no information is found about the reliability of smoke detection systems in distribution substations specifically. Hence, the reliability of smoke detection systems for general buildings is used for the assessment in Section 7.6.2. Some of the articles that do not provided the reliability of smoke detection systems for general buildings, an average value will be used from the reliabilities of smoke detectors for commercial, residential and institutional occupancies. Table 5-3 shows the reliability of smoke detection systems for general buildings based on the following literature: Bukowski, Budnick, Schemel [78], and Yung et al. [79].

Table 5-3: Reliability of smoke detection systems

Type of detector	**Reliability of smoke detection system**	**Original reference**
Smoke detector	85.7%	Warrington Delphi UK (1996)
Smoke detector	82.5%	Fire Engineering Guidelines Australia (1996)
Smoke detector	94.0%	Tokyo Fire Department (1997)
Smoke detector	89.0%	Watanabe (1979)
Smoke detector	77.8%	Bukowski, Budnick, Schemel (1999)
Smoke detector	80.0%	NRCC (2006)

Automatic suppression systems

As Thomas [80] stated, the performance of automatic sprinkler suppression systems can be defined into four categories, as follows:

1. The fire is too small to activate the sprinkler system
2. The sprinkler system should have been activated but did not
3. The sprinkler system is activated and controlled the fire but did not extinguish the fire
4. The sprinkler extinguished the fire

The first category refers to a scenario where a small fire may self-extinguish due to lack of fuel or oxygen. In this case, the smoke layer temperature is expected to be low and not sufficient to activate the sprinkler heads. However, in the case of a transformer fire initiating in a distribution substation, a sufficient fuel load is expected to be in the room, such as dielectric material, electrical equipment, power cables and the transient combustible materials. Unless the distribution substation consists of oxygen control system, which may immediately reduce the oxygen level when fire is detected, transformer fires are expected to burn continuously and to be large enough to activate the sprinkler heads. Since the use of oxygen control system is not a subject of this study, the first class is not considered to be possible in the case of transformer fires.

The three other categories are separated into two phases: success and failure. The sprinkler system is considered to have failed if it is not activated in a fire (Category 2), whereas the system is considered to be a success once it is activated regardless of it controlling or extinguishing the fire (Category 3 and Category 4). Many previous reports have proved that the leading reason for the unsatisfactory sprinkler performance is due to human error, such as failure to maintain the operational status of the system, and failure to assure the adequacy of the system for complete coverage of the current hazard. Similar to smoke detection systems, the reliability of sprinkler systems for general buildings is used for the assessment in this research due to the unavailability of data about the performance of sprinkler systems in a distribution substation. Table 5-4 shows the reliability of sprinkler systems for general buildings based on the following literature: Bukowski [78], Yung [79], Taylor [81], Spearpoint [82], Koffel [83], Budnick [84], Rohr [85], Richardson [86], Risk Logic Inc. [87], Miller [88] and Marryatt [89].

Table 5-4: Reliability of Sprinkler systems

Building occupancy	**Reliability of sprinkler system**	**Original reference**
General	95.0%	Warrington Delphi UK (1996)
General	99.0%	Fire Engineering Guidelines Australia (1996)
General	97.0%	Tokyo Fire Department (1997)
General	92.1%	BRE (1973)
General	96.2%	Powers (1979)
General	96.7%- 97.9%	Finucane et al. (1987)
General	96.0%	Bukowski, Budnick, Schemel (1999)
General	90.0%	NRCC (2006)
General	81.3%	Taylor (1990)
General	97.2%	Yashiro et al. (2000)
General	96.2%	NFPA (1970)
General	95.7%	US Navy (1977)
General	95.0%	Smith (1983)
General	87.0%	Ramachandran (1998)
General	86.1%	Factory Mutual (1977)
General	85.8%	Oregon State Fire Marshal (1978)
General	96.0%	Budnick (2001)
General	93.0%	Hall (2005)
General	96.0%	Richardson (1985)
General	82.0%	Risk Logic Inc (2006)
General	94.8% - 95.8%	Miller (1974)
General	99.5%	Marryatt (1988)

CHAPTER 6 FAULT TREE ANALYSIS

6.1 Introduction

Fault Tree Analysis (FTA) is understood to be *“a system engineering method for representing the logical combinations of various system states and possible causes which can contribute to a specified event (called the top event)”* as defined in the standard for risk management AS/NZS 4360:1999 [90]. The tree structure, which is organised by logical dependency, generally begins with the definition of a top event and then determines the probability of that event through logical relationships, such as AND gates and OR gates. In general, AND gates represent a situation where the top event is true only if all the lower events are true and is false if one of the lower events are false. Inversely, OR gates represent a situation where the top event is true if any one of the lower events is true and is false only if all of the lower events are false. Typically, the probability of the lower events can be determined in three ways; by examining the historical data, by expert engineering judgement or by evaluating the scenario by using a model. As an output of FTA, the probability of the top event can be estimated.

In this chapter, a typical fault tree is developed for a transformer fire in a distribution substation as the top event. It is a sequence of events that could lead to the transformer fire, which include the appearance of ignition sources, the appearance of combustible materials and the availability of oxygen to the fire. By providing the expected fault rate of these lower events, the probability of a transformer fire in a distribution substation can be estimated. However, due to the lack of information about the fault rate of these lower events, the probability of a transformer fire in a distribution substation is not determined but the structure of the fault tree is given for reference.

6.2 Fault Tree

Based on the information discussed in Section 2.3.4, a typical fault tree for a transformer fire in a distribution substation is developed as illustrated in Figure 6-1 through to Figure 6-3. This fault tree is provided to show the necessary elements resulting in a transformer fire in a distribution substation. Generally, three primary contributing factors must be present to result in a transformer fire. These factors are:

1. Source of fuel
2. Source of oxygen
3. Source of ignition

Any materials that have the ability to combust are considered to be potential fuels for a fire or explosion when an ignition source is provided. In distribution substations, the following combustible materials are likely to be present. These include:

- Power cables and electrical equipment directly connected to the transformer;
- Dielectric material inside the transformer, including any substances inside them;
- Transient combustible materials, such as the wooden boards and chairs;
- Combustible vapour, which is generated by oil decomposition due to overheating.

Essentially, the occurrence of the above combustion material may be affected by several factors, including the selection of materials for transformer system (e.g. non-combustible dielectric materials (dry air), high fire resistance rated cables and other electrical components), the reliability of protection systems and a good maintenance and management plan. All of the above described factors should play vital role in determining the probability of occurrence of the combustible material in the distribution substation. It should be noted that the presence of combustible material is not always sufficient to cause a fire. In terms of this study, the presence of fuel is considered to be effectively 100% otherwise no fire could occur.

As is known, fires may self-extinguish if there is not sufficient oxygen provided. The main source of oxygen for a fire or explosion is the general body of air. From the literature review, a new solution to limit transformer failure resulting in a fire has been developed and applied in many modern distribution substations. As Allan [91] stated, "*Successful designs have involved the use of closed chambers where the transformers are immersed in an inert atmosphere of nitrogen or CO2*". This solution could potentially reduce the level of oxygen below that required to support combustion in the area. In this situation, the probability of oxygen availability may rely on the oxygen control system. In other words, the presence of oxygen may be reduced. Oxygen control system and its reliability are not studied in this report..

As defined by Ainsworth et al. [92], "*A source of ignition is anything that has the potential to get hot enough to ignite a material, substance or atmosphere in the workplace*". For distribution substations, the source of ignition can be classified into internal overheat and external overheat. Internal overheating indicates that the heat is generated internally by an equipment failure, such as electrical arc or sparking, and the protection devices are defective. External overheating may include any exposure fires, such as arson, lightning strike or cable overheat due to overload or cable degradation or the like.

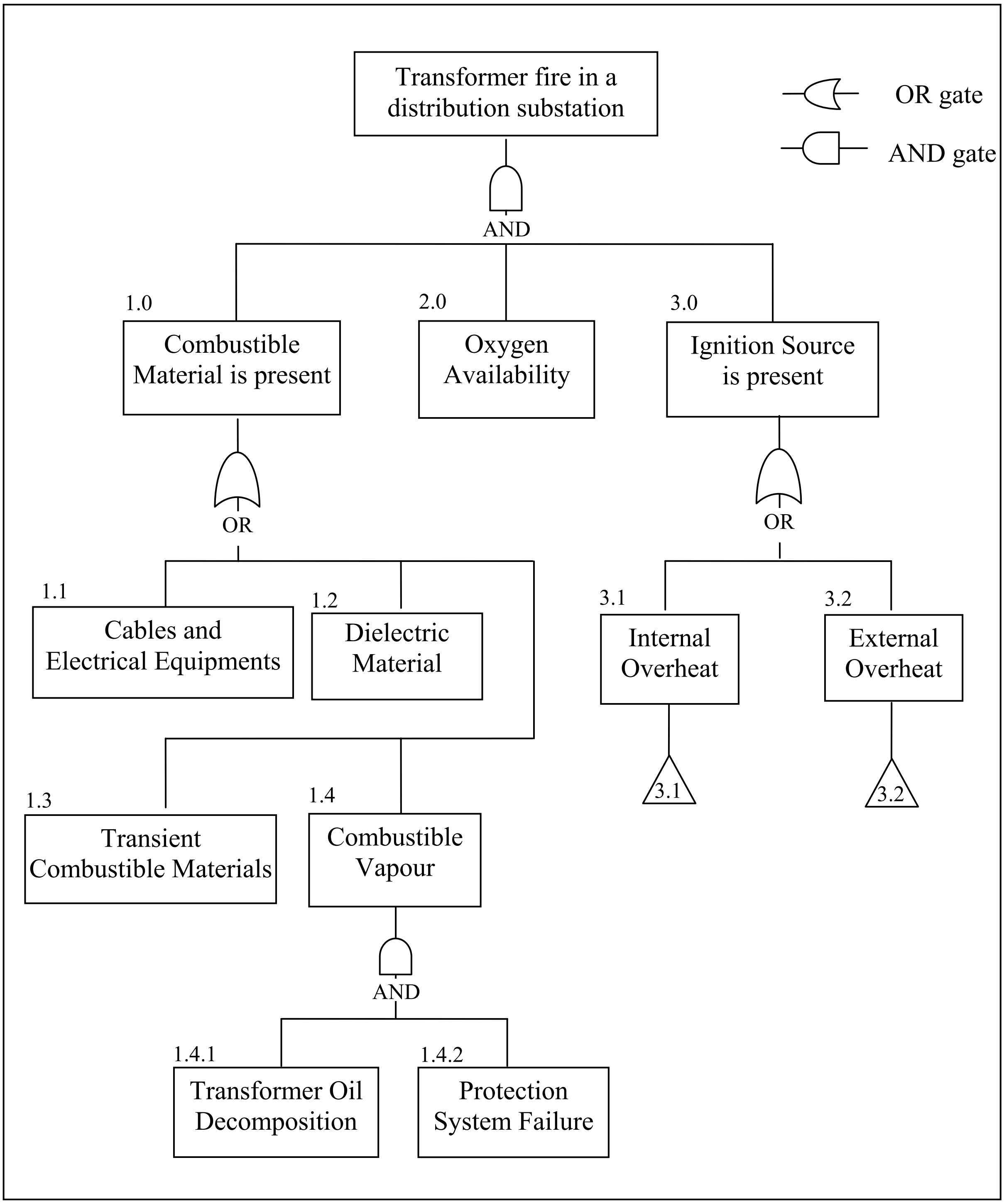


Figure 6-1: Fault tree for the transformer fire

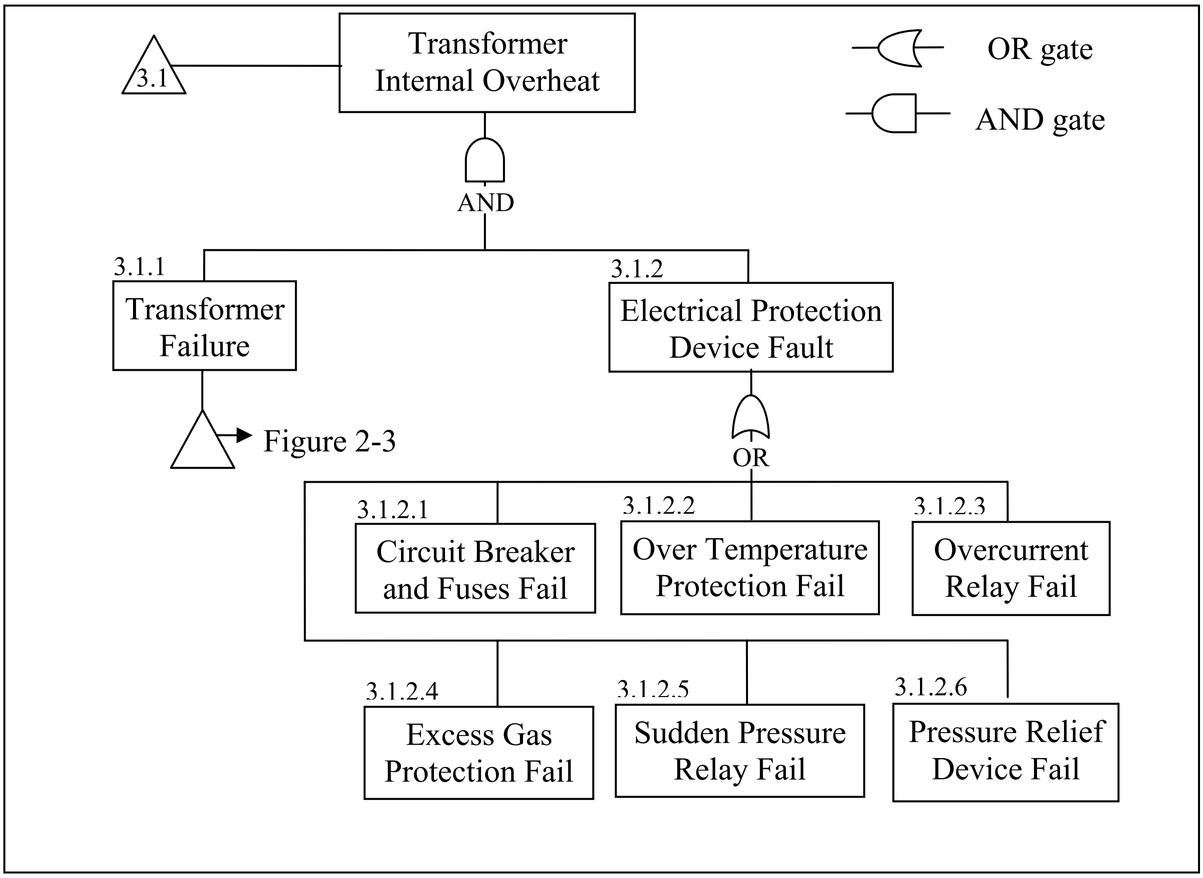


Figure 6-2: Fault tree for transformer internal overheat

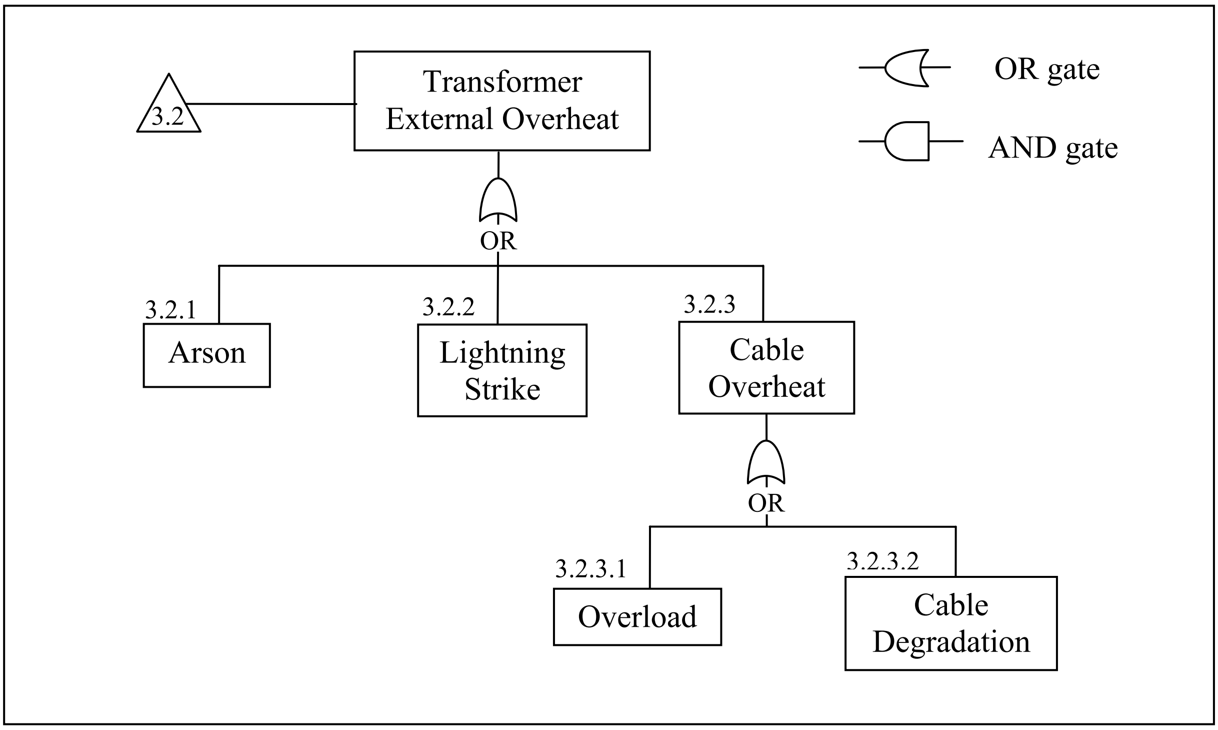


Figure 6-3: Fault tree for transformer external overheat

CHAPTER 7 EVENT TREE ANALYSIS

7.1 Introduction

The definition of risk is found in Standard AS/ NZS 4360:1999 [90]. It states that *"Risk is the chance of something happening that will have an impact upon objectives. It is measured in terms of consequences and likelihood"*. The standard further described that *"Consequences may be expressed in terms of monetary, technical or human criteria …and likelihood is usually expressed as either a probability, a frequency or a combination of exposure and probability…"*.

Event Tree Analysis (ETA), which is a primary Quantitative Risk Assessment tool, is defined in Standard AS/ NZS 4360:1999 [90]. It states that the ETA is *"a technique which describes the possible range and sequence of the outcomes which may arise from an initiating event"*. It is understood that ETA is a forward looking consequence technique. By identifying the event of hazard as a root, the following outcomes, usually two potential outcomes (success or failure), may develop in responding to the previous event and so on. Each branch probability can be obtained by the product of the probability along the pathways and life safety consequence is considered in the assessment. In order to allow a comparison between fire safety designs, the consequences are translated into equivalent monetary values (EMV). Note that the risk to building occupants is evaluated based on the number of fatalities, which is the expected maximum number of fatalities resulting from a certain accident in the scenario.

As Barry [93] stated, risk can be estimated using the following equations:

Equation 7-1: $$Risk = \begin{pmatrix} \text{Initiating Fire} \\ \text{Event} \\ \text{Likelihood(F)} \end{pmatrix} \times \begin{pmatrix} \text{Product of the probability of} \\ \text{each branch } (\mathrm{P_j}) \\ \text{where j = number of the branch} \end{pmatrix} \times \left(\text{Consequences (C)}\right)$$

Equation 7-2: $$Total \quad Risk = \sum_j F \cdot P_j \cdot C$$

The steps for developing fire risk event tree are identified by Barry [93], as follow:

1) Identifying the initiating event and the pathway factors;
2) Structuring the event tree branches and evaluate the incident outcomes;
3) Quantifying the probability for the pathway factors in each branch;
4) Quantifying the consequences and translate them into the EMV;
5) Determining the fire risk estimation and record it for the cost-benefit analysis.

From the literature review, it is found that there are two major limitations of the ETA. The first limitation of the ETA is that each event tree can only evaluate one identified initiating event with the designed pathway factors. As stated in the Risk-based Decision-making guidelines [94], "*an event tree is not an exhaustive approach for identifying various causes that can result in an accident. Other analysis techniques should be considered if the objective of the analysis is to identify the cause of potential accidents*." Generally, the initiating event and the sequence of outcomes in the event tree are to be primarily identified by other analysis techniques, such as What-if, Checklist, Hazardous Operation Assessment (HAZOP) and Failure Mode and Effects Analysis (FMEA). In the case of more than one initiating event or any changes of the pathway factors in the event tree, independent event trees are required. Based on this limitation, a total of 14 independent event trees are developed to assess the scenarios with different fire safety design and transformer types in this report.

As the second limitation of the ETA, it is often difficult to define the probabilities independently because the occurrence of the root events is usually dependent on the outcome of prior events. The probability of success/ failure of the resulting events usually correlate to the previous event. For example, if the detection system is failed, it could potentially delay the arrival time of the Fire Service and result in influence of the success/ failure probability of manual firefighting. However, many currently available data are likely to be measured individually for the use of various systems and services. Therefore, these data may be inappropriate as each event has its specific dependency in the event tree. To overcome this limitation, significant literature review may be required to make sure the use of data is appropriate.

Uncertainty is expected in the risk estimate due to the assumptions made and the uncertainties of the data sources as discussed in Section 1.3. In the assessment, probability distributions with boundaries will be used for these uncertain input parameters in the risk estimate calculation. A software package, @Risk4.5, which is an additional function in Microsoft Excel for extending the analytical capabilities of Excel, is used to conduct the Monte Carlo simulations for the risk estimates.

In addition, where an array of values is found for the pathway factors, such as the reliability of sprinkler systems and smoke detection systems, the Bestfit function in @Risk4.5 will be used to fit the best distribution to data.

7.2 Model Overview

The primarily objective of this research is to evaluate whether four hour fire separation between the distribution substation and the interior spaces of the building proposed by the NZFS is a cost-effective solution to the occupants life safety in a typical New Zealand high-rise building. Prior to the assessment, it is significant to define the characteristics of the model building and the specifications of the distribution substation. Two approaches were carried out to define a base building for the analysis. These include:

1. Site visits to the existing high-rise buildings in Christchurch, New Zealand in 2006.
2. Review of high-rise building plans.

Based on the above information, a model building with specified characterisations is defined as a base building for the analysis in this research. A brief description of the model building and the specifications of the distribution substation are listed in Table 7-1 and Table 7-2, respectively.

Table 7-1: Model building characterisation

Location of the building	- Central city
Building use	- Commercial and residential mixed-use building,
Number of storeys and building height	- The building contains 6 floors and has a total height of 21.6m with 3.6m height on each floor. - The escape height is measured up to the floor of the top level and, therefore, is 18m.
Purpose groups	- CM (retail shop) and ID (substation) at ground floor; - SR (residential apartment) at 2nd floor up to the 6th floor (Refer to Section 3.2)
Floor area	- 800m^2 per floor
Number of occupants	- Apartment floors: 6 apartments on each floor are estimated. As Haag [95] stated, the occupant density is about 2.4 persons per house. Total number of occupants in the apartments is therefore estimated to be 72 people (2.4 persons/house x 6 houses x 5

	floors) - The floor area of the retail shop is assumed to be 400m^2. Therefore, the number of occupants in the building is determined to be about 67 occupants based on 6m^2 per person for retail shop area as Bennetts et al. [96] stated. - One or two contractors are expected to work in the plant room regularly (e.g. maintenance, inspection and testing). - Other space on the ground floor is assumed to serve the corridor, lobby, lift, stairs or the like. No occupants counted as per the C/AS1 precautions.
Means of escape	- Two escape routes are provided in the building
Active systems	- According to the C/AS1 Clause 4.5.11, for SR purpose group where any lower floor contains a purpose group other than SR (e.g. CM retail shops, ID distribution substation), all lower floor shall have either Type 3 (heat detector), Type 4 (smoke detector) or Type 6 (Sprinkler). In this research, a Type 4 automatic fire alarm system with smoke detectors and manual call points is to be installed throughout the building and is monitored. - Fire hose reels, Fire hydrant system and Fire panel board are assumed to be in the building. - Depending on the fire safety design in each scenario, sprinkler systems may or may not be provided.

Table 7-2: Specifications of the distribution substation

Location of the distribution substation	The distribution substation is located on the ground floor having one external wall with an access direct to the outside and an internal access is provided to the building.
Room geometry	W4m x L6m x H3.6m
Number of transformers	One transformer (3-phase, 750kVA – 11kV/415V)
Combustible materials	Dielectric material, cables and electrical equipment, transient combustible materials and combustible vapour
Volume of oil	550 – 840 L for any liquid type transformer Oil containment is installed. (Applicable for liquid type transformer only)

Generally, distribution transformers can have power ratings of 300kVA, 500kVA, 750kVA, 1000kVA or more. Some recent researchers have found the average power consumption is about 8 to 10kVA per New Zealand household. In this case, the model building is assumed to include shops and apartments in a 6 storey building. Assuming there are 6 apartments on each floor, the total power consumption is determined to be 360kVA. To be conservative, higher total power consumption is expected. Therefore, a single 750kVA (3-phase, 11kV to 415V step-down) transformer is considered to be adapted for the model building.

Through discussion with a senior sales engineer [97], it is understood that a 750kVA liquid type transformer usually contains about 550L to 840L of transformer oil and the most likely volume of oil is about 600L. Typically, the size of a 750kVA transformer is about L 1.5m x W 1.5m x H 2m. Therefore, including the associated facilities, the floor area of the distribution substation is estimated to be about 24m^2 with a room ceiling height of 3.6m.

Two site visits were conducted to two distribution substations in New Zealand. One of which is in the Christchurch city centre and another is at the University of Canterbury. Some photographs were taken at these distribution substations as attached in Appendix A. From the site inspections, some transient combustible materials are found in distribution substations. These materials include wooden boards and furniture. Therefore, these combustible materials should be included when considering the fire loads in the distribution substations.

The model building is assumed to be a non-sprinklered building sprinkler. It is understood that in a sprinklered building, sprinkler system is likely to be extended to the distribution substation inside and the costs of this extension is expected to be low. Therefore, the cost-effectiveness of installing a sprinkler system in the distribution substation inside a sprinklered building is expected to be higher than installing a sprinkler system in the distribution substation inside a non-sprinklered building due to its low cost. To be conservative, this research assesses the risk of transformer fire in a non-sprinklered building.

Recently, many new distribution substations often separate transformers, switchgears and other low hazard electrical facilities by internal construction. This approach has two main advantages: the first advantage is to reduce the probability of the electrical contractors to work in a high risk indoor environment for a long time and another advantage is to prevent small electrical or cable fires spread to the high hazard equipment. However, this research primarily considers the fire risk exposure to the building occupants and the fire origin is the transformer (not ignited from other exposure fires). Therefore, the internal construction separating the equipment in a distribution substation is not considered to have a significant benefit to the building occupants in this case. Therefore, this research will only assess a transformer fire in a distribution substation with no internal constructions separating the equipment.

7.3 Analysis Approach

A total of 14 scenarios with different fire safety designs and transformer types for a distribution substation in a high-rise building are assessed in this research. In order to evaluate the fire risk in a distribution substation with different fire safety designs separately, the same type of transformer, Flammable liquid (mineral oil) insulated transformer, is used in the first 10 scenarios. Generally, the differences between these scenarios are the involvement of the sprinkler systems and the use of different FRR construction. Simply, sprinkler systems are considered to be either installed or not installed in the room. Five typical levels of FRR construction are assessed, which are 30 minute FRR, 1 hour FRR, 2 hour FRR, 3 hour FRR and 4 hour FRR.

Thereafter, two particular fire safety designs, i.e. 3 hour fire separation with no sprinkler systems and 1 hour fire separation with sprinkler systems, are selected as a baseline for analysing the transformer types. In Scenario 11 to Scenario 14, two types of transformers with a low fire hazard, a less flammable liquid (silicone oil) insulated transformer and a dry type (dry air) transformer, will be used to replace flammable liquid (mineral oil) insulated transformer. The reason for selecting these two fire safety designs as the baseline in this part is due to these two fire safety designs being recommended in the NFPA as mentioned in Section 3.5. Note that NFPA is the only standard provided the fire safety protection requirements for other types of transformers. A brief summary of the fire safety design and type of transformer used in each scenario is shown in Table 7-3. Note that smoke detection and alarm systems and manual Fire Service suppression are considered in all cases.

Table 7-3: A brief description of the fire protection systems combination for each scenario

Scenario	Type of transformer	Smoke detection system	Sprinkler system	Manual fire suppression system	FRR construction
1	Liquid Type (Mineral oil)	Provided	Not provided	Provided	30 minute
2	Liquid Type (Mineral oil)	Provided	Not provided	Provided	1 hour
3	Liquid Type (Mineral oil)	Provided	Not provided	Provided	2 hour
4	Liquid Type (Mineral oil)	Provided	Not provided	Provided	3 hour
5	Liquid Type (Mineral oil)	Provided	Not provided	Provided	4 hour
6	Liquid Type (Mineral oil)	Provided	Provided	Provided	30 minute
7	Liquid Type (Mineral oil)	Provided	Provided	Provided	1 hour
8	Liquid Type (Mineral oil)	Provided	Provided	Provided	2 hour
9	Liquid Type (Mineral oil)	Provided	Provided	Provided	3 hour
10	Liquid Type (Mineral oil)	Provided	Provided	Provided	4 hour
4a	Liquid Type (Silicone oil)	Provided	Not provided	Provided	3 hour
4b	Dry Type (Dry air)	Provided	Not provided	Provided	3 hour
7a	Liquid type (Silicone oil)	Provided	Provided	Provided	1 hour
7b	Dry Type (Dir air)	Provided	Provided	Provided	1 hour

7.4 Identifying the Initiating Event and the Pathway Factors

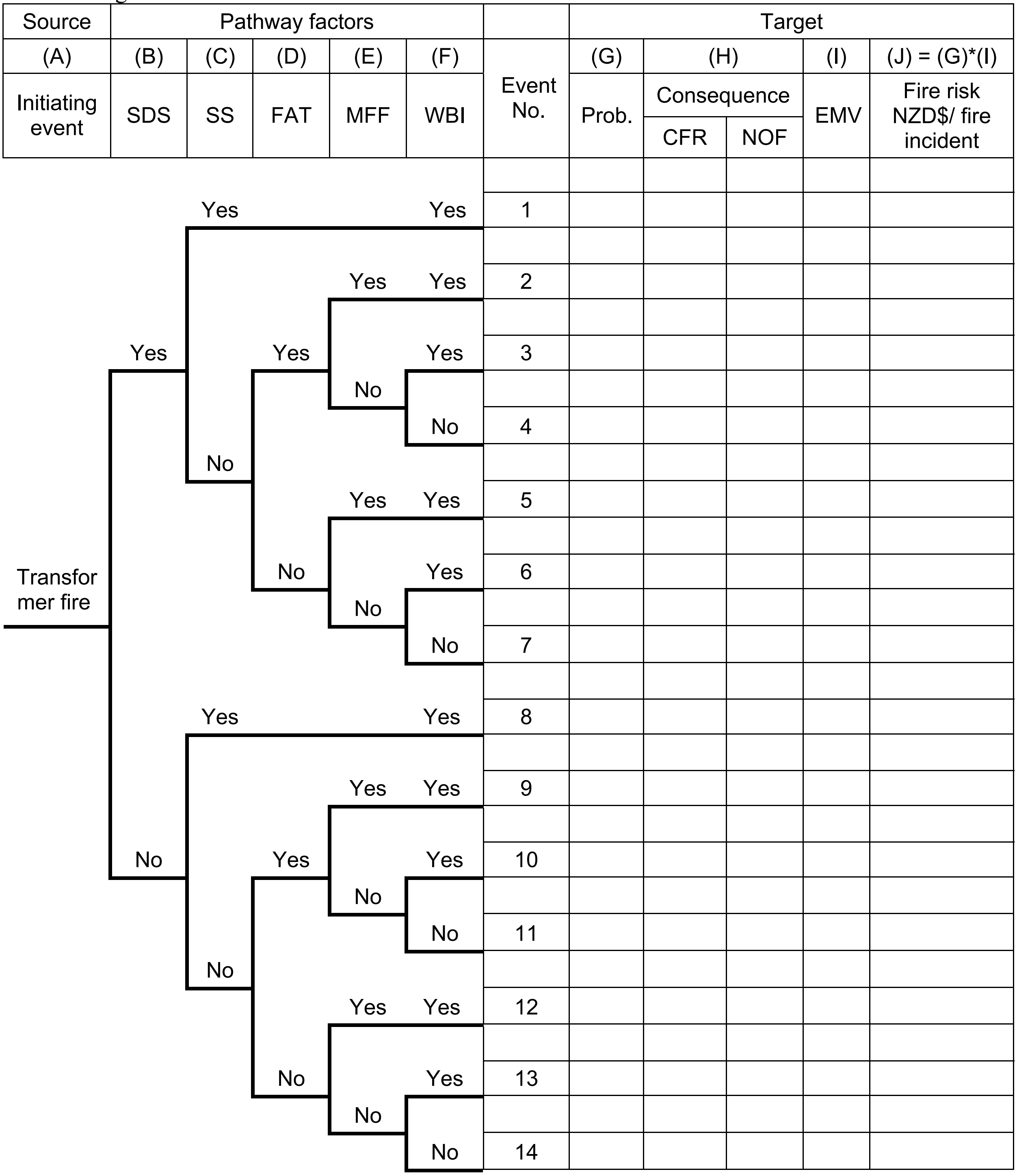
As discussed earlier in the report, the major cause of transformer failure is insulation breakdown / arcing, which may rupture the transformer tank, releasing the oil and then igniting the dielectric material once it is exposed to oxygen. In this research, a transformer fire in a distribution substation is assumed to be the initial event. The pathway factors of the event tree are developed as follow:

- Smoke detection system (SDS) - Success/ Failure
- Sprinkler system (SS) - Success/ Failure or not installed
- Manual Fire Service suppression, which is further separated into two parts:
  - Firefighters' action time (FAT): the time between when the Fire Service is alerted and when the firefighters start to fight the fire (t_{a_a}) is less than 10 minutes - Success/ Failure
  - Manual Fire Fighting (MFF) - Success/ Failure
- Wall barrier integrity maintained (WBI) - Success/ Failure

7.5 Structuring the Event Tree Branch Logic

The structure of the event tree for transformer fires in distribution substations is shown in Figure 7-1. The event tree logic is read off from the source (A) on the left hand side, through the pathways (B - F) to the targets (G - J). There are two outcome segments, Yes/No, for each pathway factors, where 'Yes' implies success and 'No' implies failure. The probability of the various consequences is then calculated by multiplying together the various branch probabilities of each factor. Consequence levels are measured based on the number of fatalities (NOF) and the civilian fatality rate (CFR) (Refer to Section 7.7). In order to allow the fire risks to be combined, the consequence are converted to equivalent monetary values (EMV) using the value of statistical life (VSL) in Aldy and Viscusi [98]. Finally, the total risk (J) of a transformer fire in a distribution substation is estimated by multiplying the probability and the EMV consequence as described in Equation 7-2. A brief description for each of the outcome events of the event tree is illustrated in Table 7-4.

Figure 7-1: Structure of the event tree for a transformer fire in a distribution substation



where:

SDS = Smoke detection system

SS = Sprinkler system

FAT = Firefighters' action time

MFF = Manual fire fighting

WBI = Wall barrier integrity maintained

Prob. = Probability

CFR = Civilian fatality rate

NOF = Number of fatalities

EMV = Equivalent Monetary Value

Table 7-4: A brief description for each of the 14 outcome events

Outcome event		Description of the event
1	Smoke Detection System : Success Sprinkler System : Success Firefighter Action Time : [1](See note below) Manual Fire Fighting : [1](See note below) Wall Barrier Integrity : Success	- Fire is detected by both smoke detectors and sprinkler heads; - Early detection and fire alarm is expected; - Fire is controlled by sprinkler systems; - Fire may not be suppressed immediately but confinement in the distribution substation is expected;
2	Smoke Detection System : Success Sprinkler System : Failure Firefighter Action Time : Success Manual Fire Fighting : Success Wall Barrier Integrity : Success	- Fire is detected by smoke detectors; - Early detection and fire alarm is expected; - Firefighters take action to fight the fire within 10 minutes since the Fire Service is alerted (Involvement of firefighters in the earlier stage); - Fire is controlled by the firefighters; - Fire may not be suppressed immediately but confinement in the distribution substation is expected;
3	Smoke Detection System : Success Sprinkler System : Failure Firefighter Action Time : Success Manual Fire Fighting : Failure Wall Barrier Integrity : Success	- Fire is detected by smoke detectors; - Early detection and fire alarm is expected; - Firefighters take action to fight the fire within 10 minutes since the Fire Service is alerted (Involvement of firefighters in the earlier stage); - Fire is out of control; - Fire is confined to the distribution substation but smoke may spread out of the room;
4	Smoke Detection System : Success Sprinkler System : Failure Firefighter Action Time : Success Manual Fire Fighting : Failure Wall Barrier Integrity : Failure	- Fire is detected by smoke detectors; - Early detection and fire alarm is expected; - Firefighters take action to fight the fire within 10 minutes since the Fire Service is alerted (Involvement of firefighters in the earlier stage); - Fire is out of control and is not confined to the distribution substation; - Outbreak fire occurred. Both fire and smoke may spread beyond the distribution substation;
5	Smoke Detection System : Success Sprinkler System : Failure Firefighter Action Time : Failure Manual Fire Fighting : Success Wall Barrier Integrity : Success	- Fire is detected by smoke detectors; - Early detection and fire alarm is expected; - Firefighters take more than 10 minutes to start the fire suppression; - Fire is controlled by the firefighters; - Fire may not be suppressed immediately but confinement in the distribution substation is expected;

Table 7-4 continued

Outcome event		Description of the event
6	Smoke Detection System : Success Sprinkler System : Failure Firefighter Action Time : Failure Manual Fire Fighting : Failure Wall Barrier Integrity : Success	- Fire is detected by smoke detectors; - Early detection and fire alarm is expected; - Firefighters take more than 10 minutes to start the fire suppression; - Fire is out of control; - Fire is confined to the distribution substation but smoke may spread out of the room;
7	Smoke Detection System : Success Sprinkler System : Failure Firefighter Action Time : Failure Manual Fire Fighting : Failure Wall Barrier Integrity : Failure	- Fire is detected by smoke detectors; - Early detection and fire alarm is expected; - Firefighters take more than 10 minutes to start the fire suppression; - Fire is out of control and is not confined to the distribution substation; - Outbreak fire occurred. Both fire and smoke may spread beyond the distribution substation;
8	Smoke Detection System : Failure Sprinkler System : Success Firefighter Action Time : [1](See note below) Manual Fire Fighting : [1](See note below) Wall Barrier Integrity : Success	- Fire is detected by the sprinkler heads; - Early detection and fire alarm is expected; - Fire is controlled by sprinkler systems; - Fire may not be suppressed immediately but confinement in the distribution substation is expected;
9	Smoke Detection System : Failure Sprinkler System : Failure Firefighter Action Time : Success Manual Fire Fighting : Success Wall Barrier Integrity : Success	- Fire is not detected by any fire safety systems; - No early detection and fire alarm provided; - Firefighters take action to fight the fire within 10 minutes since the Fire Service is alerted (Involvement of firefighters in the earlier stage); - Fire is controlled by the firefighters; - Fire may not be suppressed immediately but confinement in the distribution substation is expected;
10	Smoke Detection System : Failure Sprinkler System : Failure Firefighter Action Time : Success Manual Fire Fighting : Failure Wall Barrier Integrity : Success	- Fire is not detected by any fire safety systems; - No early detection and fire alarm provided; - Firefighters take action to fight the fire within 10 minutes since the Fire Service is alerted (Involvement of firefighters in the earlier stage); - Fire is out of control; - Fire is confined to the distribution substation but smoke may spread out of the room;

Table 7-4 continued

Outcome event		**Description of the event**
11	Smoke Detection System : Failure Sprinkler System : Failure Firefighter Action Time : Success Manual Fire Fighting : Failure Wall Barrier Integrity : Failure	- Fire is not detected by any fire safety systems; - No early detection and fire alarm provided; - Firefighters take action to fight the fire within 10 minutes since the Fire Service is alerted (Involvement of firefighters in the earlier stage); - Fire is out of control and is not confined to the distribution substation; - Outbreak fire occurred. Both fire and smoke may spread beyond the distribution substation;
12	Smoke Detection System : Failure Sprinkler System : Failure Firefighter Action Time : Failure Manual Fire Fighting : Success Wall Barrier Integrity : Success	- Fire is not detected by any fire safety systems; - No early detection and fire alarm provided; - Firefighters take more than 10 minutes to start the fire suppression; - Fire is controlled by the firefighters; - Fire may not be suppressed immediately but confinement in the distribution substation is expected;
13	Smoke Detection System : Failure Sprinkler System : Failure Firefighter Action Time : Failure Manual Fire Fighting : Failure Wall Barrier Integrity : Success	- Fire is not detected by any fire safety systems; - No early detection and fire alarm provided; - Firefighters take more than 10 minutes to start the fire suppression; - Fire is out of control; - Fire is confined to the distribution substation but smoke may spread out of the room;
14	Smoke Detection System : Failure Sprinkler System : Failure Firefighter Action Time : Failure Manual Fire Fighting : Failure Wall Barrier Integrity : Failure	- Fire is not detected by any fire safety systems; - No early detection and fire alarm provided; - Firefighters take more than 10 minutes to start the fire suppression; - Fire is out of control and is not confined to the distribution substation; - Outbreak fire occurred. Both fire and smoke may spread beyond the distribution substation;

---

[1] Manual Fire Service suppression is expected to be success in the case of sprinkler controlled fire regardless the intervention time and firefighters' ability. Hence, success or failure of the FAT and the MFF is not considered to be necessary.

7.6 Quantification of the Branch Line Probabilities

7.6.1 Initiating Event Likelihood

Initiating event likelihood means the frequency of the initiating event occurring. In the assessment, a transformer fire in a distribution substation is considered as the initiating event. This research is particularly interested in the effects once a transformer fire occurs. To be conservative, the likelihood of a transformer fire is assumed to be one (100%). In other words, the event that a transformer fire has occurred in a distribution substation inside a building is investigated.

7.6.2 Smoke Detection System (SDS)

Smoke detection systems are intended to:

1) Detect fire by smoke;
2) Provide an early warning alarm to the building occupants;
3) Alert the Fire Service;
4) Activate other fire protection systems (e.g. fire dampers and smoke exhaust systems).

Hence, good reliability of smoke detection systems can provide a reasonable level of protection to the safety of the building occupants. It is understood that the performance of smoke detection systems is generally high in case of transformer fires. Unlike domestic smoke detection systems, where the system performance is often affected by lack of power supply or delay due to the distance to the fire (as the Government of Alberta [99] stated), smoke detection systems in distribution substations are expected to be more efficient due to back-up power supply being provided and the room area being relatively small so the location of smoke detectors should be close to the transformer. In an event of a liquid type transformer fire in a distribution substation, a transformer oil fire is expected. According to the research by Heskestad and Dobson [51], HRR and toxic smoke released by a transformer oil fire should be large enough to activate the smoke detectors installed in the room. Hence, the reliability of the smoke detection systems in a distribution substation is expected to be relatively high.

The figure below shows the probability distribution of the performance of smoke detection system reliability for general buildings. As stated in the Data Collection section, the reliability data for a smoke detection system was obtained from two articles. Out of these data, a minimum of 77.8%, a maximum of 94% and an average of 84.8% are observed. Due to the lack of available data, a triangular distribution is considered in the assessment.

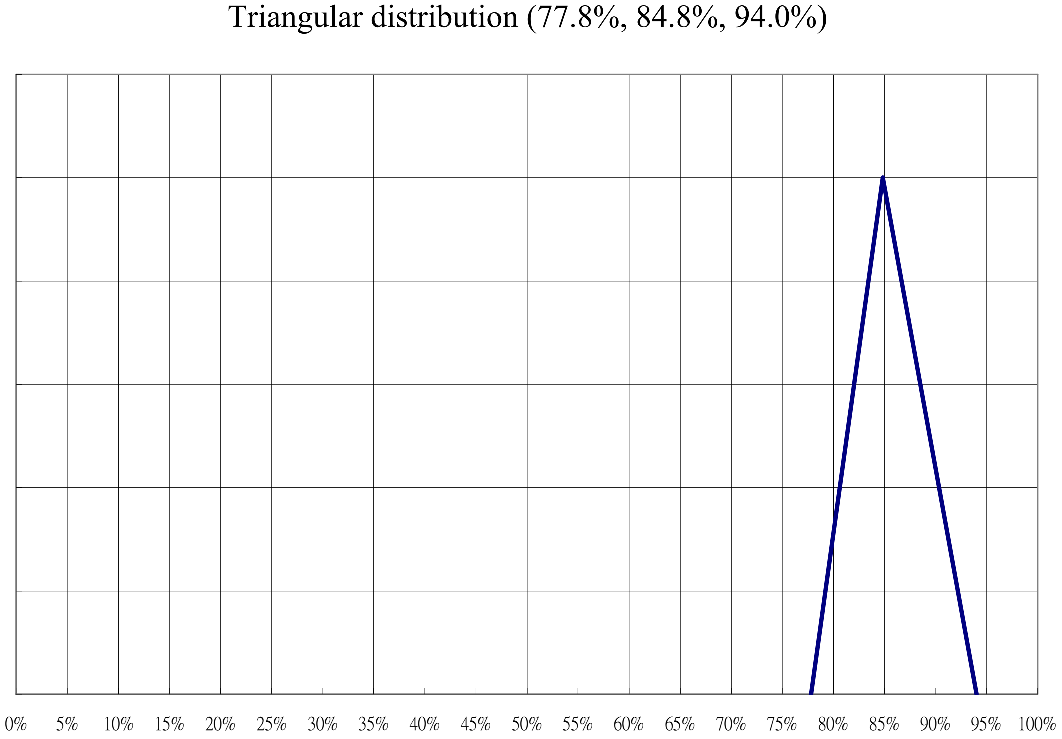


Figure 7-2: Probability distribution of the performance of smoke detection systems

Table 7-5: Summary of the probability distribution of the performance of smoke detection systems

Distribution types and parameters	Triangular distribution
Maximum	94%
Minimum	77.8%
Mean	84.8%

7.6.3 Sprinkler System (SS)

Sprinkler systems are intended to:

1) Detect fire by hot smoke;
2) Provide an early warning alarm to the building occupants;
3) Provide an early suppression (control) to the fire;
4) Alert the Fire Service.

Sprinkler systems are known to be very effective and efficient systems to suppress or control a fire. They activate when temperatures surrounding the sprinkler head reaches the sprinkler activation temperature. As discussed in Section 5.2.2, a fuel load is expected in the distribution substation, including dielectric material, electrical equipment, power cables and the transient combustible materials. Hence, transformer fires are very unlikely to be too small to activate the sprinkler systems as the first category in Thomas [80]. Thereforem, transformer fires are considered to be large enough to activate the sprinkler heads unless the sprinkler systems are defective or damaged.

The figure below shows the probability distribution of the performance of sprinkler system reliability for general buildings. As stated in the Data Collection section, the reliability data for a sprinkler system was obtained from a total of 11 articles. Out of these data, a minimum of 81.3%, a maximum of 99.5% and an average of 93.4% are observed. Due to the lack of available data, a triangular distribution is considered in the assessment.

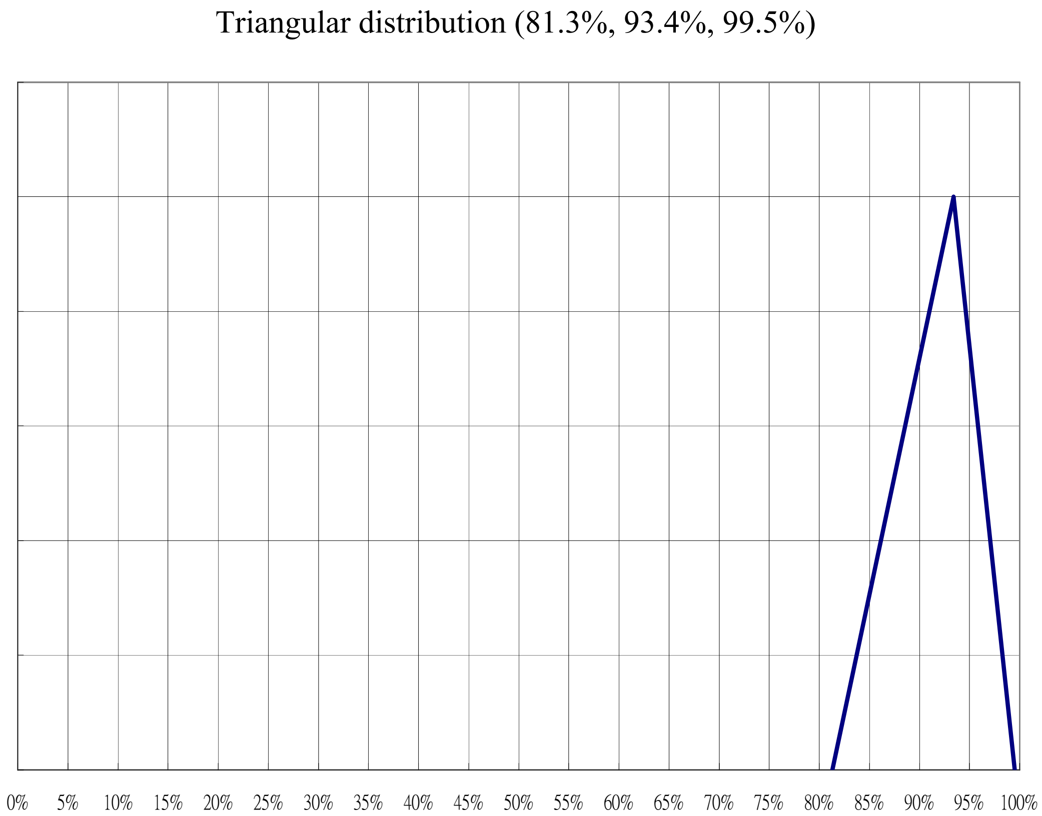

Triangular distribution (81.3%, 93.4%, 99.5%)

Figure 7-3: Probability distribution of the performance of sprinkler system

Table 7-6: Summary of the probability distribution of the performance of sprinkler system

Distribution types and parameters	Triangular distribution
Maximum	99.5%
Minimum	81.3%
Mean	93.4%

7.6.4 Manual Fire Service Suppression – Firefighter Action Time (FAT)

The probability of the time between when the Fire Service is alerted and when the firefighters start to fight the fire, t_{a_a}, is less than 10 minutes (P_{FAT}) is measured based on the results of the NZFS FIRS statistical data analysis. According to the 20 fire incidents reported to the NZFS FIRS with respect to fires initiating in distribution substations, the time between the Fire Service being alerted and the firefighters starting to take action to fight the fire is often delayed due to traffic congestion or other interventions. For example, more than half of these fire incidents [65] have reported that the firefighters are required to wait for the power to be isolated before they can start the fire suppression and in one case, the firefighters took almost 8 minutes in traffic.

It is understood that the earlier firefighters start attacking the fire, the higher the chance that they can manage to control and suppress the fire. In this research, the critical time between the Fire Service being alerted and the firefighters starting taking action to fight the fire is considered to be 10 minutes, as Fontana et al. [100] stated. Based on the NZFS FIRS statistical data, the probability that the Fire Service can start trying to suppress the transformer fire within 10 minutes from receiving an alarm signal (P_{FAT}) is examined in Table 7-7. As defined in Section 7.2, the fire protection systems in the building are to be monitored. The Fire Service is expected to be alerted either by a fire alarm or an emergency call.

Table 7-7: Probability that t_{a_a} less or more than 10 minutes

Year	Number of distribution substation fires	Number of these fires that t_{a_a} < 10 minutes	Probability of FAT success	Probability of FAT failure
January 2000 - January 2001	4	2	50%	50%
January 2001 - January 2002	0	0	N/A	N/A
January 2002 - January 2003	5	4	80%	20%
January 2003 - January 2004	4	1	25%	75%
January 2004 - January 2005	3	0	0%	100%
January 2005 - January 2006	4	2	50%	50%

From the available data above, it is found that the minimum, maximum and average (mean) of the probability of FAT success are of 0%, 80% and 41%, respectively; while the minimum, maximum and average (mean) of the probability of FAT failure are of 100%, 20% and 59%. The following figures show the triangular distributions for the probability of success and failure of the FAT

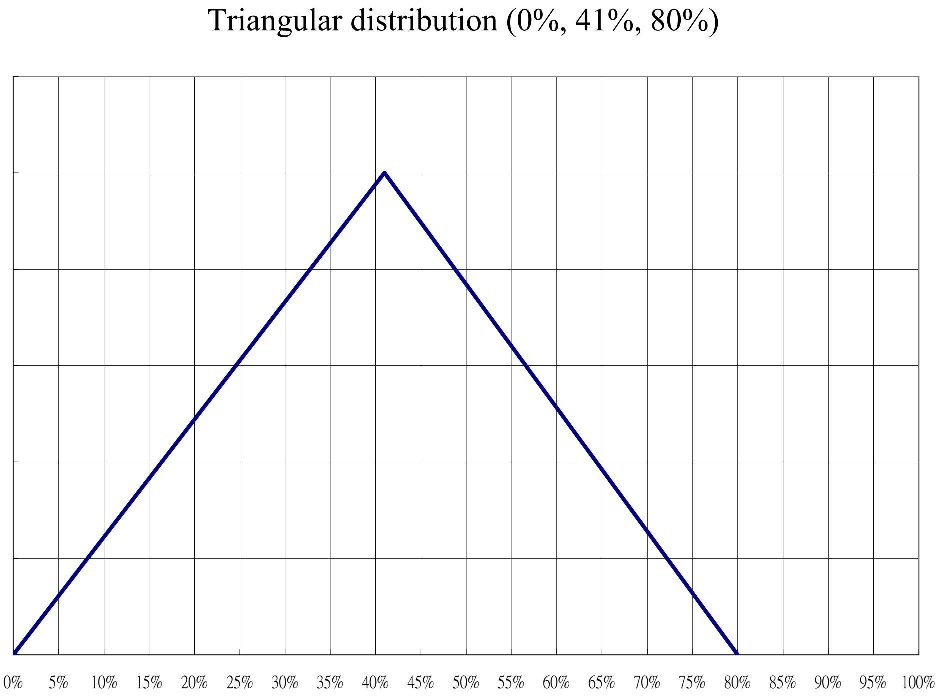


Figure 7-4: Probability distribution of FAT – success (P_{FAT_S})

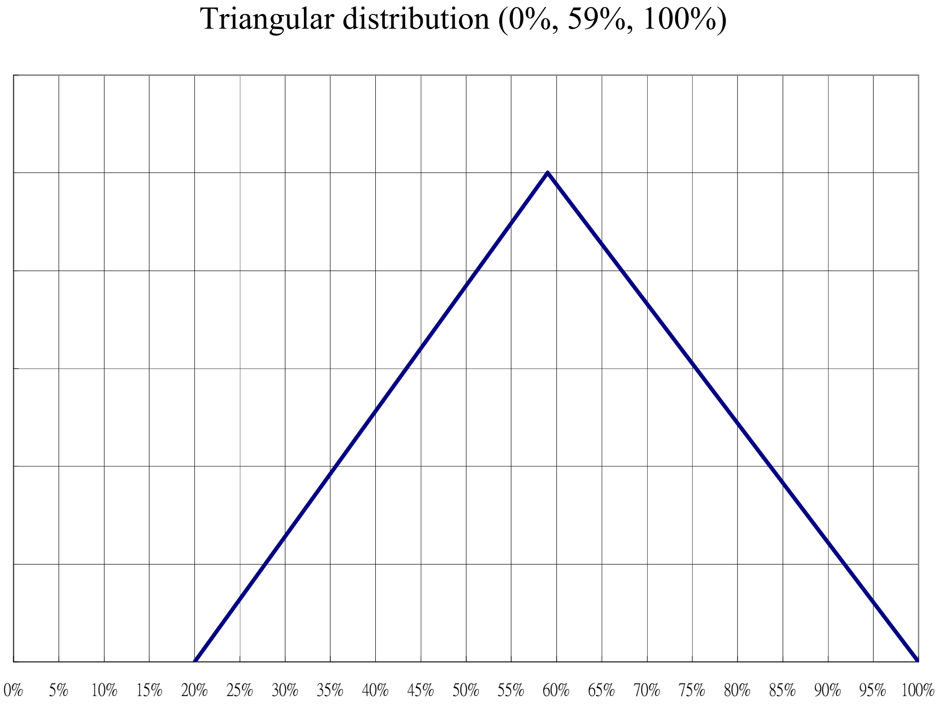


Figure 7-5: Probability distribution of FAT– failure (P_{FAT_F})

Table 7-8: Summary of the probability distribution of firefighters' action time

	Probability distribution of FAT – success (less than 10 minutes)	Probability distribution of FAT – failure (more than 10 minutes)
Distribution types and parameters	Triangular distribution	Triangular distribution
Maximum	80%	100%
Minimum	0%	20%
Mean	41%	59%

7.6.5 Manual Fire Service Suppression – Manual Fire Fighting (MFF)

Fontana et al. [100] state that the probability that the Fire Service can control the fire (P_{MFF}) depends on the ability of the firefighters and the alarm time. Based on the data found in Fontana et al. [100], the P_{MFF} in general buildings is estimated (Refer to Appendix D). As the results show, the P_{MFF} is determined to be in the range of 67.4% (volunteer non-professional firefighters and the t_{a_a} more than 10 minute) to 98.8% (full training professional firefighters and the t_{a_a} less than 10 minute). Table 7-9 shows the P_{MFF} in different situations where the ability of firefighters and the early warning alarm are considered.

Table 7-9: P_{MFF} in general buildings

In general building		**Probability of MFF success to control the fire (P_{MFF_S})**		**Probability of MFF fail to control the fire (P_{MFF_F})**	
Firefighters' ability	**Early warning alarm**	**$t_{a\text{-}a}$ less than 10 min**	**$t_{a\text{-}a}$ more than 10 min**	**$t_{a\text{-}a}$ less than 10 min**	**$t_{a\text{-}a}$ more than 10 min**
Professional firefighters	Not provided	80.0% - 95.0%	71.6% - 85.0%	5% - 20%	5% - 29.4%
Non-professional firefighters	Not provided	75.8% - 90.0%	67.4% - 80.0%	10% - 14.2%	20% - 32.6%
Professional firefighters	Provide	83.2% - 98.8%	81.1% - 96.3%	1.2% - 17.8%	3.7% - 18.9%
Non-professional firefighters	Provide	82.1% - 97.5%	71.6% - 85.0%	2.5% - 17.9%	15% - 28.4%

From the literature, it is found that about 9,000 firefighters are distributed over 400 fire stations in New Zealand. The Fire Service annual report 2005 [101] states there are a total of 1607 career (professional) firefighters in New Zealand, 2005. As defined in Section 7.2, the model building is to be located in the central city and hence is considered to be acceptable to assume the building being protected by professional firefighters, rather the volunteer (non-professional) firefighters. As a result, the P_{MFF} for professional firefighters in Table 7-9 are selected for this assessment.

Through discussion with a senior fire station officer in Victoria Fire Service [102], it is understood that the P_{MFF} given in Table 7-9 seem applicable in the event of general electrical fires (e.g. dry type transformer), rather transformer oil fires, and the P_{MFF} of transformer oil fire should be lower. As known, oil fire can be controlled once the oil temperature is lower than its flash point. According to the studies on the transformer dielectric fluids in Section 4.8, it is understood that typical mineral oil and silicone oil have the minimum flash point of 100°C and 300°C, respectively. As advised by the senior fire station officer [102], the P_{MFF} of less flammable oil fires and flammable oil fires may reduce approximately 4 to 5% and 10 to 12%, respectively, from the P_{MFF} of general electrical fires (Note that the mean value is used for the assessment, i.e. the P_{MFF} is reduced by 4.5% for less flammable oil fires and 11% for flammable oil fires). Hence, the P_{MFF} for different types of transformer are summarised in Table 7-10.

Table 7-10: Probability distribution of manual fire fighting performance

Smoke Detection System (SDS)	Firefighter Action Time (FAT)	Manual Fire Fighting (MFF)	P_{MFF} for different transformer types installed		
			Flammable liquid insulated (mineral oil)	Less flammable liquid insulated (silicone oil)	Dry type (dry air)
Success	Success (less than 10 minutes)	Success	72.2% - 87.8%	78.7% - 94.3%	83.2% - 98.8%
		Failure	12.2% - 27.8%	5.7% - 21.3%	1.2% - 16.8%
Success	Failure (more than 10 minutes)	Success	70.1% - 85.3%	76.6% - 91.8%	81.1% - 96.3%
		Failure	14.7% - 29.9%	8.2% - 23.4%	3.7% - 18.9%
Failure	Success (less than 10 minutes)	Success	69.0% - 84.0%	75.5% - 90.5%	80.0% - 95.0%
		Failure	16.0% - 31.0%	9.5% - 24.5%	5.0% - 20.0%
Failure	Failure (more than 10 minutes)	Success	60.6% - 74.0%	67.1% - 80.5%	71.6% - 85.0%
		Failure	26.0% - 39.4%	19.5% - 32.9%	15.0% - 28.4%

7.6.6 Wall Barrier Integrity Maintained (WBI)

The primary purposes of fire separation construction are:

1) To prevent spread of fire to other parts of the building;
2) To maintain the buildings structural integrity;
3) To provide a sufficient tenability along escape routes for some specified period of time.

The selection of the fire resistance rating (FRR) for building construction often depends on the fire load density, ventilation factor and conversion factor, as mentioned in the Fire Engineering Design Guide [32]. In order to estimate the probability of the wall barrier integrity being maintained (P_{WBI}), it is necessary to determine the probability of the equivalent time of fire exposure. If the equivalent time of fire exposure is over the provided FRR, the wall barrier is considered to have failed to maintain the construction integrity. By the same reasoning, if the provided FRR is over the equivalent time of fire exposure the wall barrier is considered to have maintained its integrity.

The fire loads in a distribution substation containing a liquid type transformer may vary significantly. Depending on the rupture point of the tank, the expected amount of transformer oil released from the tank may be different. For example, if the rupture point is at the bottom of the tank, the tank of oil is expected to be released; whereas if the rupture point is on the top of the tank, the amount of transformer oil released from the tank is less.

Literature have indicated that tank rupture, as a result of internal transformer failure such as arcing, is likely to occur round at the top edge of the tank. In that case, only a small amount of the contained dielectric fluids would be expected to be released from the tank; in other words, the fuel loads exposed in the transformer room would also be relatively low. However, no relevant studies, researches or statistical data were found to support this phenomenon. Therefore, to be conservative, the assessment assumes at that least half the tank of transformer oil (50%) would be released in the case of a fire but that the transformer oil is most likely to be released completely (100%).

According to a reference by ABB Power Transmission Pty Ltd. [103], it is understood that typical dry type transformers often contain less than 5% of combustible materials compared to the liquid type transformer. To be conservative, the fuel loads in a dry type transformer is considered to be determined by multiplying 5% with the fuel loads in a flammable liquid (mineral oil) insulated transformer. Hence, the probability of equivalent time of fire exposure for dry type transformer installed can be determined.

The calculation of the equivalent time of fire exposure (t_e) is discussed in the C/AS1, as follows:

Equation 7-3: $t_e = e_f \times k_b \times w_f$

where w_f is the ventilation factor

e_f is the fire load density in the design area (MJ/m^2 floor area)

k_b is a conversion factor

Fire load density in a distribution substation (e_f):

A typical fire load density for power stations and transformer winding occupancy was found to be 600MJ/m^2 from the Fire Engineering Design Guide [32]. However, this value is given without providing any specific details, such as the number of transformers in the station, the power rating of the transformers, the type of dielectric material, the volume of transformer oil or the size of transformer. Hence, a more specific fire load density for a distribution substation containing a single 750kVA transformer is determined using the following equations from the Fire Engineering Design Guide [32]:

Equation 7-4: $e_f = \frac{E}{A_f}$

Equation 7-5: $E = \sum_i \left(M_i \times H_{C_i}\right)$

Equation 7-6: $M_i = D_i \times (a \times V_i)$

where E is the total fuel load in the design area (MJ)

A_f is the floor area (m^2)

M_i is the mass of the fuel, *i* (kg)

H_c is the heat of combustion of the fuel, *i* (MJ/kg)

D_i is the density of the fuel, *i* (kg/m^3)

V_i is the volume of the fuel, *i* (m^3)

a is the fraction of oil released (0.5 for 50% oil released and 1 for 100% oil released)

i is the type of fuel

Based on the literature reviews and the site visits, it was found that the major combustible material in a distribution substation consists of dielectric fluid (e.g. transformer oil), wood products (e.g. wooden hardboard, furniture), electrical components and power cables (e.g. PVC). Through discussion with a senior sales engineer [97], it is understood that a 750kVA liquid type transformer usually contains about 550L (0.55 m^3) to 840L (0.84 m^3) of transformer oil and the most likely volume of oil is about 600L (0.60 m^3). In addition to the total amount of the contained dielectric fluid in a transformer, a factor is to be introduced to the calculation. This factor is to predict the percentage of the contained dielectric fluid is likely to be released in the event of a fire. However, due to a lack of available information, the conservatism is to assume that at least half the tank of transformer oil, 50% (minimum), would be released but that the transformer oil is most likely to be released completely, 100% (most likely value and maximum). Considering the floor area of the distribution substation is 24 m^2, the volumes of the wood products and the power cables (assuming a total of 15 m of 35 mm^2 and 10 m of 185 mm^2 thick copper cables) are estimated to be about 0.16 m^3 and 0.0024 m^3, respectively. The density and heat of combustion of transformer oils are referred to Section 4.8. Furthermore, the density and the heat of combustion for the wood products and the power cables are found to be 720 kg/m^3 and 19.8 MJ/kg and 1710 kg/m^3 and 16 MJ/kg, respectively. Table 7-11 indicates the input parameters and values for determining the fire load density.

Table 7-11: Input parameters and values for determining the fire load density

	Mineral oil	**Silicone oil**	**Wood products**	**Power cables**
Density, kg/m^3	830 – 890	960 – 1100	720	1710
*Volume, m^3	0.55 - 0.84 (0.6)	0.55 - 0.84 (0.6)	0.16	0.0024
Likelihood to be present in a transformer room in the event of a fire (est. %)	50%- 100% (100%)	50%- 100% (100%)	100%	100%
Heat of Combustion, MJ/kg	45.9	28	19.8	16.0

*Note that the values in the brackets imply the most likely value

Ventilation factor (w_f):

This factor may be calculated by knowing the dimensions of the floor area, wall/roof opening and height of the room. The equations are shown as follow:

Equation 7-7:

$$w_f = \left(\frac{6.0}{H}\right)^{0.3}\left[0.62 + \frac{90\cdot(0.4-\alpha_v)^4}{1+b_v\alpha_h}\right] > 0.5$$

Equation 7-8:

$$\alpha_v = \frac{A_v}{A_f} \qquad 0.025 < \alpha_v < 0.25$$

Equation 7-9:

$$\alpha_h = \frac{A_h}{A_f} \qquad \alpha_h \leq 0.20$$

Equation 7-10:

$$b_v = 12.5\cdot(1+10\alpha_v - \alpha_v^2)$$

where
H	is the height of the distribution substation (m)
A_v	is the area of wall openings (m^2)
A_h	is the area of roof openings (m^2)
A_f	is the floor area (m^2)
α_v	is the ratio of the area of wall opening to the floor area
α_h	is the ratio of the area of roof opening to the floor area

In the model, the floor area of the distribution substation is defined as 24 m^2, 4 m by 6 m, with a height of 3.6 m. The size of wall openings is estimated based on the expected wall leakage, such as cable penetrations or doorways. As defined in Section 7.2, two 1.98 m by

0.8 m single doors, one internal exit via the building and one direct access to the outside, are to be installed in the distribution substation. The expected minimum wall opening is 0.1 m^2 assuming there is improper sealed cable penetration or leakage through the doorways; and the expected maximum wall opening is 3.2 m^2 assuming both the single doors are fully opened in the case of a fire. However, it is considered to be very likely to have both doors fully opened in an event of a transformer fire and it is known the smaller the wall openings, the higher the ventilation factor and the higher the equivalent time of fire exposure would be. Therefore, to be conservative, the most likely wall opening is assumed to be 0.5 m^2; one single door partially opened during fire.

Due to the general restriction of openings on the roof in a distribution substation, the roof openings are likely to be small. However, small leakages may occur due to improper sealed cable penetrations and the venting system where the automatic fire damper may be defective or not installed. Therefore, the area of roof opening is assumed to be in the range of 0.01 m^2 and 0.1 m^2 and is a uniform distribution. Table 7-12 indicates the input parameters and values for determining the ventilation factor.

Table 7-12: Input parameter and values for determining the ventilation factor

Floor area (m^2)	24
Height of roof (m)	3.6
Area of wall openings (m^2)	Triangular distribution 0.1 – 3.2 (0.5)
Area of roof openings (m^2)	Uniform distribution 0.01 – 0.1

Conversion factor (k_b):

Conversion factor is determined based on the use of the construction materials in the distribution substations. By knowing the thermal inertia (kρc) of the distribution substation construction materials, the conversion factor can be found from the table given in the Fire Engineering Design Guide [32]. For a high-rise building, 21.6m high, the building is generally constructed with concrete, but in some cases brick and masonry may be used instead. Because selection of the construction materials may vary in different buildings, the construction material is not defined in this study. Instead, sensitivity analysis was carried out to analysis the effects of the conversion factor on the overall results of the equivalent time calculation using the @Risk4.5.

As a result of the sensitivity analysis, it was found that conversion factor may change the result of equivalent time of fire exposure by about 25% to 25.7%, depending on the type of insulation fluid and the construction materials installed. This change is considered to be significant in the measurement of the equivalent time. Therefore, a range of thermal inertia is used to cover the thermal inertia of three possible construction materials (concrete, brick and masonry). Uniform distribution is used for the conversion factor with the boundaries of 0.065 (lightweight concrete ceiling and floor, plasterboard walls) and 0.08 (Normal concrete ceiling and floor, plasterboard walls). Note the values of thermal conductivity (k), density (ρ) and specific heat (c) for these construction materials are found from Karlsson [104].

Overall, the equation for the equivalent time can be rewritten by substituting Equation 7-8 through Equation 7-10 into Equation 7-7, as follows:

Equation 7-11:

$$t_e = \frac{k_b \times w_f}{A_f} \cdot \left[\left(D_{oil} \cdot (a \cdot V_{oil}) \cdot Hc_{oil} \right) + \left(D_{wood} \cdot V_{wood} \cdot Hc_{wood} \right) + \left(D_{cable} \cdot V_{cable} \cdot Hc_{cable} \right) \right]$$

Due to the involvement of the probability distributions as listed in Table 7-13, the equivalent time of fire exposure (t_e) is determined using @Risk4.5. Using a trial-and-error method, the result is found to have no significant differences when the number of iterations is above 5,000.

Table 7-13: The input probability distributions for the calculation of equivalent time

Input parameters	Unit	Probability distribution			
		Distribution types	Min. value	Most likely value	Max. value
Area of wall openings (A_v)	m^2	Triangular distribution	0.1	0.5	3.2
Area of roof openings (A_h)	m^2	Uniform distribution	0.01	*Not required*	0.1
Density of mineral oils (D_{oil})	kg/m^3	Uniform distribution	830	*Not required*	890
Density of silicone oils (D_{oil})	kg/m^3	Uniform distribution	960	*Not required*	1100
Total volume of the oil contain (Voil)	m3	Triangular distribution	0.55	0.60	0.84
Est. % of oil to be released from a transformer in the event of a fire	-----	Triangular distribution	0.50	1.0	1.0
Conversion factor (kb)	-----	Uniform distribution	0.65	Not required	0.08

* Most likely value is not required for Uniform distribution.

The probability of the wall barrier integrity being maintained (P_{WBI}) can be determined based on the probability distribution of the equivalent time of fire exposure. Several standard FRR constructions are selected to be assessed, such as FRR of 30 minute, 1 hour, 2 hour, 3 hour and 4 hour. These FRR levels are considered as the critical time for the wall barrier to maintain its integrity. In other words, when the equivalent time exceeds the critical time of the selected standard FRR, the wall barrier is considered to fail.

A summary of the overall results is shown in Table 7-14.

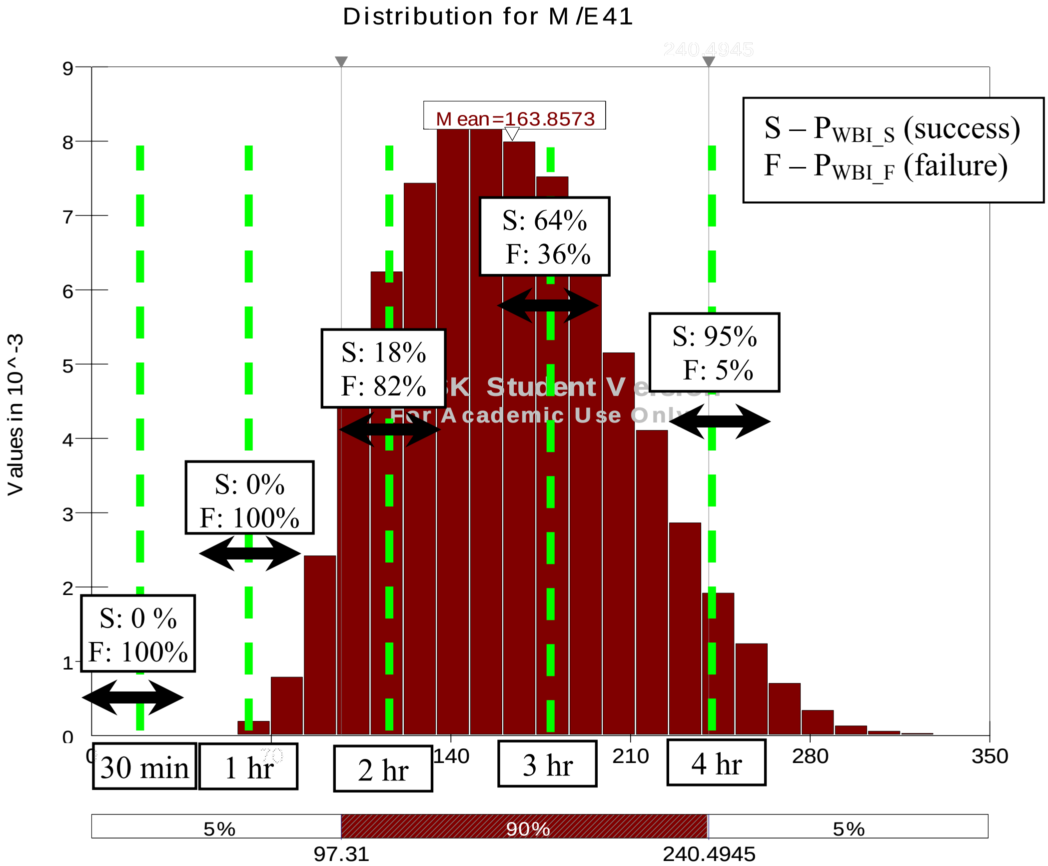


Figure 7-6: Probability distribution of equivalent time for transformer with mineral oil

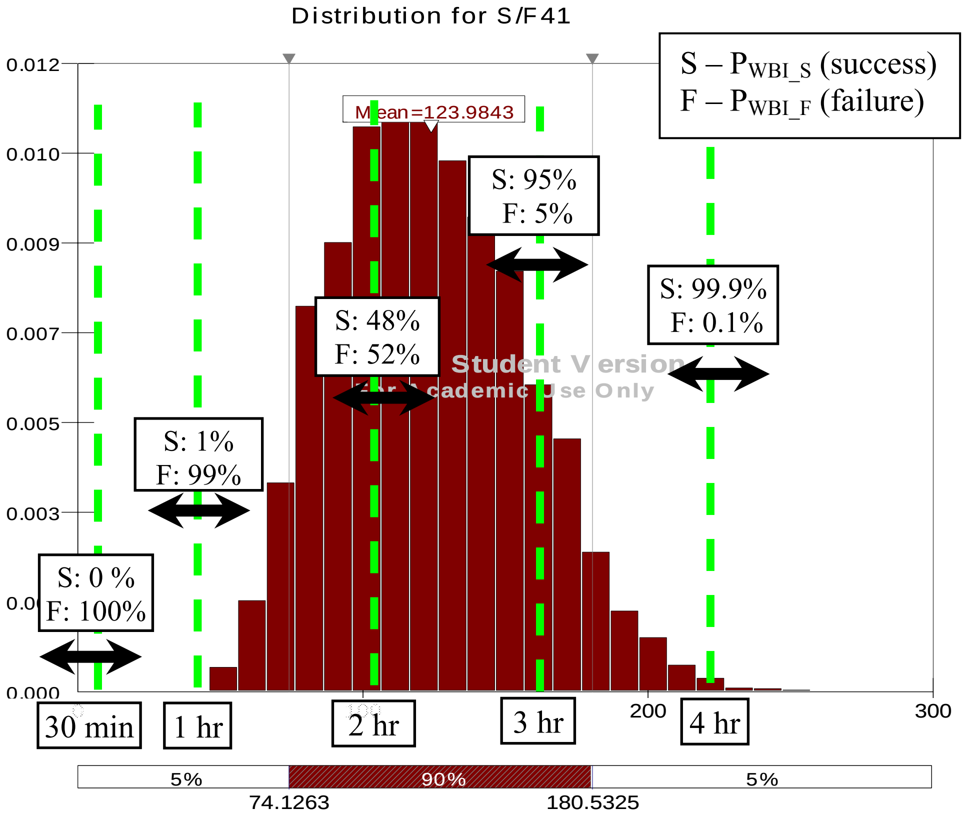


Figure 7-7: Probability distribution of equivalent time for transformer with silicone oil

As ABB Power Transmission Pty. Ltd. [103] stated, typical dry type transformer often contain less than 5% of combustible materials compared to the liquid type transformers. To be conservative, the fuel loads in a dry type transformer is considered to be determined by multiplying 5% with the fuel loads in a flammable liquid (mineral oil) insulated transformer. Therefore, the probability of equivalent time of fire exposure for dry type transformer installed is determined as follows:

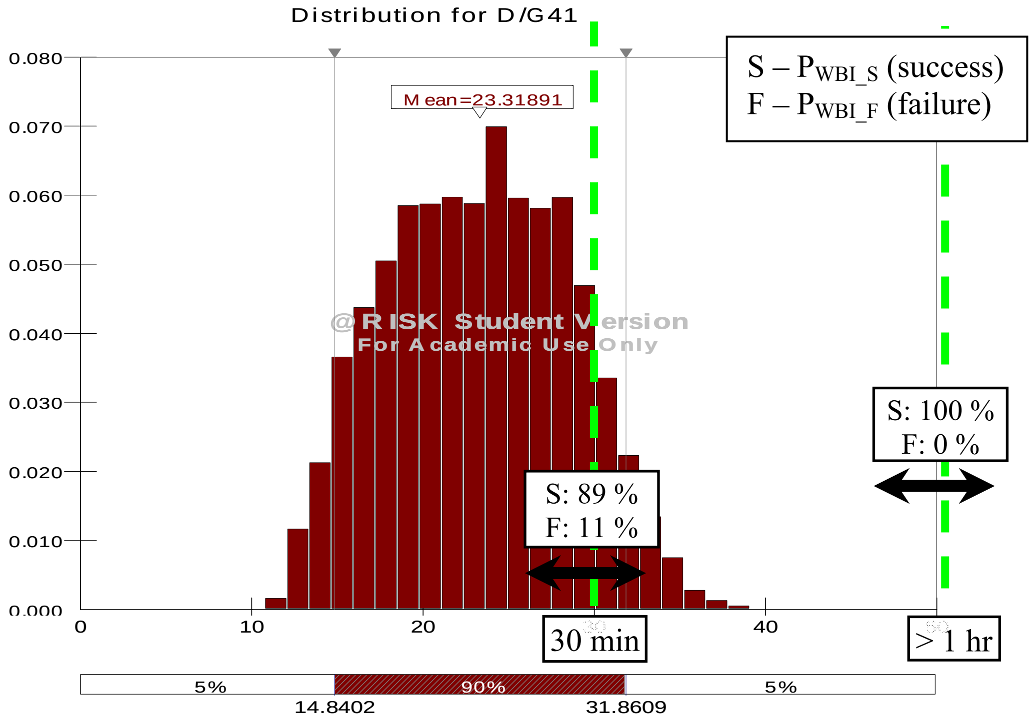


Figure 7-8: Probability distribution of equivalent time for transformer with dry type dielectric material

Table 7-14: Summary of the probability distribution of wall barrier integrity maintained (P_{WBI})

FRR construction	**WBI**	**Flammable liquid insulated transformer installed (mineral oil)**	**Less flammable liquid insulated transformer installed (silicone oil)**	**Dry type transformer installed (dry air)**
30 minute	Success	0%	0%	89%
	Failure	100%	100%	11%
1 hour	Success	0%	1%	100%
	Failure	100%	99%	0%
2 hour	Success	18%	48%	100%
	Failure	82%	52%	0%
3 hour	Success	64%	95%	100%
	Failure	36%	5%	0%
4 hour	Success	95%	100%	100%
	Failure	5%	0%	0%

7.6.7 Summary of the Probability Distributions for the Pathway Factors

An overall summary of the probability distributions for the pathway factors in each scenario with a short description are shown in Table 7-15. The incident outcomes in each scenario are classified into four groups as follows:

Group 1) Sprinkler systems success: This is the best case scenario. The sprinkler systems are in service and operating as intended in the event of a fire. Sprinkler heads, as a thermal detection system, are expected to detect the fire as well as providing an early suppression to control fire spread. Hence, the loss expectancy is considered to be normal. Occupants are expected to escape with no injuries. Fire damage to the object of origin is expected.

Group 2) Sprinkler systems fail but manual Fire Service suppression is a success: This situation is considered as a selected probable case. In this case, the sprinkler system is defective, fails to operate or is just not installed in the first place, but the firefighters are able to control the fire. However, the fire may spread to other parts of the room. The probable maximum loss is expected and the fire damage to parts of the room shall be addressed. Life safety is not considered to be significant in this situation. No injuries are expected.

Group 3) Both automatic and manual suppression measure fail but the fire is successfully confined to the room of origin: This situation is considered as a selected probable case. The probable maximum loss is expected and the fire damage to the entire room of origin shall be addressed. Life safety is addressed in this case.

Group 4) All fire safety protection systems fail (uncontrolled fire), which is the worst case scenario: All detection and protection features are assumed to be out of service or ineffective and the FRR construction fails to limit the fire to the room. Hence, maximum foreseeable loss is expected and fire damage beyond the room of origin may occur. Health and life safety may be threatened.

Table 7-15: Overall summary of the probability distributions for the pathway factors

Pathway factor	Description	Relevant scenarios	Success	[1]Failure
SDS (Refer to Section 7.6.2)	System installed, the probability of the system reliability is expressed as a triangular distribution	All scenarios	Triangular distribution (0.78, 0.85, 0.94)	Triangular distribution (0.06, 0.15, 0.22)
SS (Refer to Section 7.6.3)	System not installed	Scenario 1 – 5, 4a, 4b	0%	100%
	System installed, the probability of the system reliability is expressed as a triangular distribution	Scenario 6 – 10, 7a, 7b	Triangular distribution (0.81, 0.93, 1)	Triangular distribution (0, 0.07, 0.19)
FAT (Refer to Section 7.6.4)	The time between the Fire Service being alerted and the firefighters starting to take action to fight the fire (t_{a_a}) is less than 10min. Triangular distribution is obtained for the probabilities based on the NZFS FRIS data. This factor is appropriate for all scenarios.	All scenarios	Triangular distribution (0, 0.41, 0.8)	Triangular distribution (0.2, 0.59, 1)

[1] Note that sum of the success and failure probability for the same factor should be equal to one. To avoid confliction occur (success and failure probability for a same factor do not equal to one) while the Monte Carlo simulation, the probability distribution of success is used in the simulation and the probability of failure is simply equal to one minus the probability of success, i.e. P (failure) = 1 - P (Success). However, the probability distributions of failure are given for reference.

Table 7-15 continued

Pathway factor	Description		Relevant scenarios	Success	[1] Failure
[2] MFF (Refer to Section 7.6.5)	Case 1: SDS success FAT success	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	Uniform distribution (0.72, 0.88)	Uniform distribution (0.12, 0.28)
		b) Less flammable liquid insulated transformer (Silicone oil)	Scenario 4a, 7a	Uniform distribution (0.79, 0.94)	Uniform distribution (0.06 0.21)
		c) Dry type transformer (Dry air)	Scenario 4b, 7b	Uniform distribution (0.83, 0.99)	Uniform distribution (0.01, 0.17)
	Case 2: SDS success FAT failure	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	Uniform distribution (0.70, 0.85)	Uniform distribution (0.15, 0.30)
		b) Less flammable liquid insulated transformer (Silicone oil)	Scenario 4a, 7a	Uniform distribution (0.77, 0.92)	Uniform distribution (0.08, 0.23)
		c) Dry type transformer (Dry air)	Scenario 4b, 7b	Uniform distribution (0.81, 0.96)	Uniform distribution (0.04, 0.19)
	Case 3: SDS failure FAT success	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	Uniform distribution (0.69, 0.84)	Uniform distribution (0.16, 0.31)
		b) Less flammable liquid insulated transformer (Silicone oil)	Scenario 4a, 7a	Uniform distribution (0.76, 0.91)	Uniform distribution (0.09, 0.24)
		c) Dry type transformer (Dry air)	Scenario 4b, 7b	Uniform distribution (0.80, 0.95)	Uniform distribution (0.05, 0.20)
	Case 4: SDS failure FAT failure	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	Uniform distribution (0.61, 0.74)	Uniform distribution (0.26, 0.39)
		b) Less flammable liquid insulated transformer (Silicone oil)	Scenario 4a, 7a	Uniform distribution (0.67, 0.81)	Uniform distribution (0.19, 0.33)
		c) Dry type transformer (Dry air)	Scenario 4b, 7b	Uniform distribution (0.72, 0.85)	Uniform distribution (0.15, 0.28)

[2] Note that all four cases are expected to be used in all scenarios. The difference between the four cases is a combination of early earning system (i.e. SDS) and the intervention time (i.e. FAT). These events are expected in each of the scenarios and; therefore, all four cases are to be used in the assessment for each scenario.

Table 7-15 continued

Pathway factor	Description		Relevant scenarios	Success	[1]Failure
[3] WBI (Refer to Section 7.6.6)	Case 1: Construction having a FRR of **30 minute**	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	0%	100%
	Case 2: Construction having a FRR of **1 hour**	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	0%	100%
		b) Less flammable liquid insulated transformer (Silicone oil)	Scenario 7a	1%	99%
		c) Dry type transformer (Dry air)	Scenario 7b	100%	0%
	Case 3: Construction having a FRR of **2 hour**	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	18%	82%
	Case 4: Construction having a FRR of **3 hour**	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	64%	36%
		b) Less flammable liquid insulated transformer (Silicone oil)	Scenario 4a	95%	5%
		c) Dry type transformer (Dry air)	Scenario 4b	100%	0%
	Case 5: Construction having a FRR of **4 hour**	a) Flammable liquid insulated transformer (Mineral oil)	Scenario 1 – 10	95%	5%

[3] Note that only construction having a FRR of 1 hour and 3 hour is further assessed in Scenario 7a and 7b and Scenario 4a and 4b with different transformer types. Hence, the P_{WBI} for these scenarios are also included in the table above.

7.7 Quantification of the Consequence

7.7.1 Introduction

Consequence of fire can generally be categorized into one of the followings:

- Property damage
- Life safety exposure
- Business interruption
- Environmental impact

However, for the purpose of this research, only the life safety exposure is examined as consequences in fire. To determine the life safety consequence, two significant parameters are considered. These are the rates of civilian fatalities and injuries in fire and the value of statistical life (VSL).

7.7.2 Rate of civilian fatalities and injuries

In this chapter, the rate of civilian fatalities and injuries for each outcome event from the event tree analysis are determined based on the effectiveness of various combinations of fire safety systems in the building. This approach has also been introduced in Thomas [80].

Thomas [80] has studied the effectiveness of several fire safety systems in fires reported to the NFIRS between 1983 and 1995. In the study, it compared the consequence of fires for the various occupancies and with the various combinations of sprinkle, detector and FRR construction presence with respects to the number of fire fighter and civilian casualties and estimated property losses. The effectiveness of sprinkler, detector and FRR construction in reducing death and injury for residential apartments and retails is extracted from Thomas [80] and reproduced in Table 7-16.

Note that in comparison with the life safety consequence of distribution substation fires between 1980 and 2002 reported to the NFIRS as indicated in Table 5-1 (2.1 to 2.8 fatalities per 1000 fire and 39 to 57 injuries per 1000 fire), the rate of casualties in Thomas study is considered to be more conservative (2.8 to 11 fatalities per 1000 fire and 90 to 117 injuries per 1000 fire).

Table 7-16: Rate of casualties in residential apartment and retail areas with various combinations of fire safety systems

Detector	Sprinkler	FRR construction	Rate of civilian fatalities per 1000 fires	Rate of civilian injury per 1000 fires
Present	Present	Present	2.8	90.4
Present	Absent	Present	6.8	109.4
Present	Absent	Absent	8.7	116.8
Absent	Present	Present	3.7	76.8
Absent	Absent	Present	8.3	95.5
Absent	Absent	Absent	11	102.6

The total rates of civilian fatalities and injuries per fire for each outcome event from the Event Tree Analysis are shown in Table 7-17. As expected, in the event of sprinkler or MFF control fire, the FRR construction is considered to be able to withstand the fire; therefore, the rate of casualties of Event 2 is assumed to be equal to Event 3 (also applies to Event 5 / Event 6, Event 9 / Event 10 and Event 12 / Event 13).

Moreover, the pathway factor of FAT is expected to affect the probability of manual fire fighting (MFF) only and it was included during the likelihood calculation, and therefore, the civilian fatality rate of Event 2 is assumed to be equal to Event 5 (also applies to Event 3 / Event 6, Event 4 / Event 7, Event 9 / Event 12, Event 10 / Event 13 and Event 11 / Event 14)

Table 7-17: Rate of casualties per fire in the model building with various combinations of fire safety systems for each outcome event.

Initiating event	SDS	SS	FAT	MFF	WBI	Event No.	Rate of civilian fatality per fire	Rate of civilian injury per fire
Transformer fire	Yes	Yes			Yes	1	2.8×10^{-3}	90.4×10^{-3}
		No	Yes	Yes	Yes	2	6.8×10^{-3}	109.4×10^{-3}
				No	Yes	3	6.8×10^{-3}	109.4×10^{-3}
					No	4	8.7×10^{-3}	116.8×10^{-3}
			No	Yes	Yes	5	6.8×10^{-3}	109.4×10^{-3}
				No	Yes	6	6.8×10^{-3}	109.4×10^{-3}
					No	7	8.7×10^{-3}	116.8×10^{-3}
	No	Yes			Yes	8	3.7×10^{-3}	76.8×10^{-3}
		No	Yes	Yes	Yes	9	8.3×10^{-3}	95.5×10^{-3}
				No	Yes	10	8.3×10^{-3}	95.5×10^{-3}
					No	11	11.0×10^{-3}	102.6×10^{-3}
			No	Yes	Yes	12	8.3×10^{-3}	95.5×10^{-3}
				No	Yes	13	8.3×10^{-3}	95.5×10^{-3}
					No	14	11.0×10^{-3}	102.6×10^{-3}

7.7.3 Value of statistical life

To estimate the total risk of a transformer fire, these outcome events must have a common unit. One typical way is to translate the outcome event into the equivalent monetary value (EMV). From the literature review, it is understood that the approach of placing a value on casualties in fire has been questioned by relevant stakeholders. However, Office of the Deputy Prime Minister (ODPM) [105] and Ashe W. et al. [106] have indicated that indeed, such values are implicit in decision made for many organizations, in particular for Department of Transport (e.g. decision on whether to fund a road improvement), Department of Fire Service (e.g. how much to spend on the fire protection systems versus the life safety consequence) as well as the medical insurance companies and the like.

In addition, Krupnick [107] also stated that the value of statistical life (VSL) is an expression of the preference of reducing the risk of death (in monetary terms). Therefore, in this research, the civilian fatalities and injuries are to be translated to an equivalent monetary value (EMV) for the cost-benefit analysis.

Depending on the age group, educational qualification and wealth, the value of a statistical life in 2002 to 2006 is found to be in a range of NZD $1.9 million and NZD $15million from ODPM [105] (United Kingdom), Ashe [106] (Australia), Slayter [108] (Australia), Danish Emergency Management Agency (DEMA) [109] (Denmark), Ministry of Transport [110] (New Zealand), Aldy and Viscusi [98] (USA), Krupnick [107] (USA) and a text book, Barry [93] (USA). Considering these studies, the values used in this research are $3 million for the value of a fatality and $ 250,000 for the value of an injury.

7.7.4 Consequence of a fire

As the result, the life safety consequence of all 14 outcome events is translated to an EMV as indicated in Table 7-18.

Table 7-18: EMV for the life safety consequence of each outcome events

Event No.	Rate of civilian fatality per fire	Value of a fatality	Rate of civilian injury per fire	Value of an injury	Equivalent Monetary Value (EMV) NZD$
1	0.0028	$3,000,000	0.0944	$250,000	$32,000
2	0.0068	$3,000,000	0.1094	$250,000	$47,750
3	0.0068	$3,000,000	0.1094	$250,000	$47,750
4	0.0087	$3,000,000	0.1168	$250,000	$55,300
5	0.0068	$3,000,000	0.1094	$250,000	$47,750
6	0.0068	$3,000,000	0.1094	$250,000	$47,750
7	0.0087	$3,000,000	0.1168	$250,000	$55,300
8	0.0037	$3,000,000	0.0768	$250,000	$30,300
9	0.0083	$3,000,000	0.0955	$250,000	$48,775
10	0.0083	$3,000,000	0.0955	$250,000	$48,775
11	0.0110	$3,000,000	0.1026	$250,000	$58,650
12	0.0083	$3,000,000	0.0955	$250,000	$48,775
13	0.0083	$3,000,000	0.0955	$250,000	$48,775
14	0.0110	$3,000,000	0.1026	$250,000	$58,650

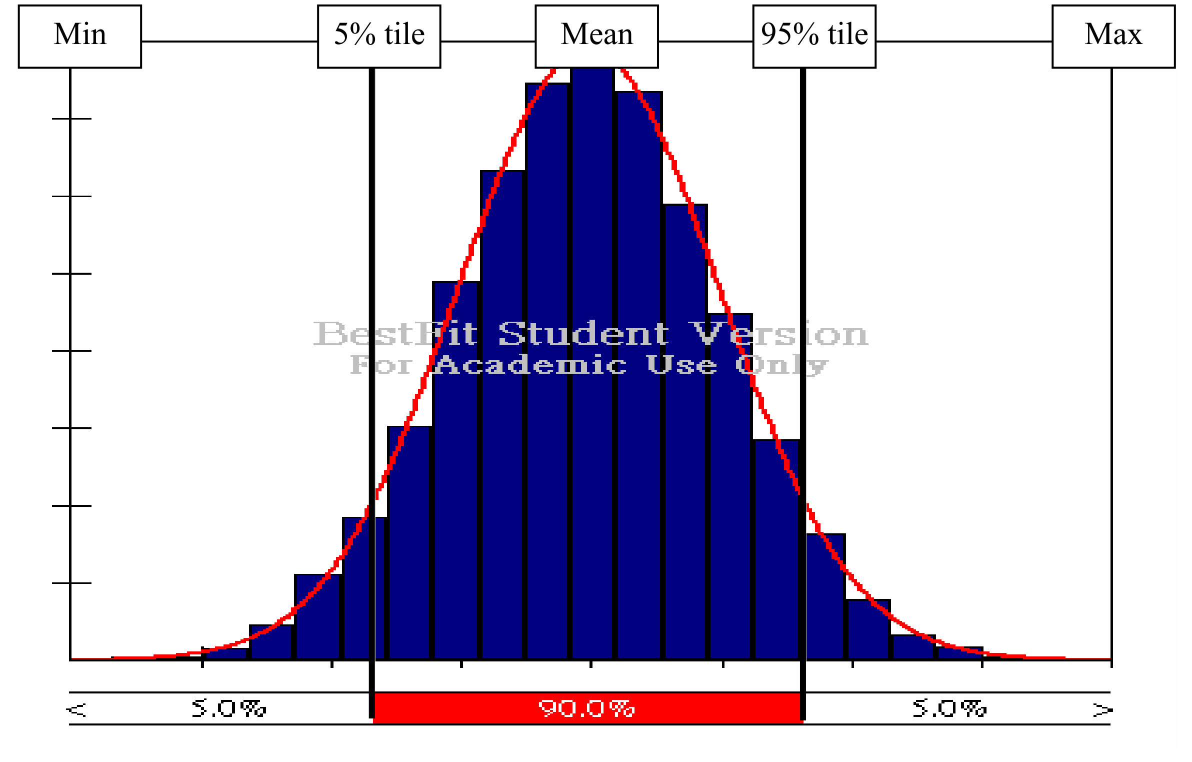
7.8 Fire Risk Estimation

Risk estimation is a process for assigning the frequencies and consequences of the hazardous event into various levels of risk. It can be expressed in terms of the likelihood of incident outcomes (outcomes probability) and the consequences (translated into the EMV) as illustrated in Equation 7-2. The probability distributions for each of the pathway factors have been introduced in Section 7.6.2 through to Section 7.6.6. Based on these defined probability distributions, Monte Carlo simulations for the fire risk estimation were conducted using @Risk4.5 as discussed in Section 7.1. In the simulations, the settings generally follow the default choice except for the sampling type and the number of iterations.

In the simulations, “Monte Carlo” is selected as the type of sampling. For the number of iterations, a trial-and-error method is used. It is found that the results would have no significant differences when the number of iterations rises above 5,000. Hence, 5,000 iterations are considered to be sufficient for the simulation. A summary of the statistical values of the total risk (NZD$/ fire incident) for each scenario is shown in Table 7-19 (Refer to Appendix E).

Note that this research primarily assumed that the fire protection required by the compliance document (C/AS1) is considered as the minimum requirements in the assessment, such as installing smoke detection and alarm systems and a minimum of 30 minute fire separation between the distribution substation and the interior spaces of the building. Scenario 1, which has the minimum fire protection requirements, is expected to have the highest risk compared to other scenarios.

Table 7-19: summary of the statistical values of the total risk (NZD$/fire incident) for each scenario



	Total risk: NZD$/ fire incident **$R_e$ (existing risk of the base case) or R_m (modified risk of the alternative)**					
	Mean	Standard Deviation	5% tile	95% tile	Min	Max
Scenario 1 (Base case 1)	49,690	240	49,310	50,080	49,013	50,450
Scenario 2	49,690	240	49,310	50,080	49,010	50,450
Scenario 3	49,330	190	49,030	49,650	48,780	49,950
Scenario 4	48,620	100	48,450	48,790	48,310	48,960
Scenario 5	47,990	40	47,920	48,050	47,890	48,090
Scenario 6	32,520	710	31,440	33,800	30,990	34,460
Scenario 7	32,520	710	31,440	33,800	30,990	34,460
Scenario 8	32,490	700	31,430	33,740	30,990	34,380
Scenario 9	32,420	670	31,400	33,620	30,980	34,210
Scenario 10	32,370	650	31,390	33,530	30,980	34,060
Scenario 4 (Base case 2)	48,620	100	48,450	48,790	48,310	48,960
Scenario 4a	47,960	40	47,900	48,030	47,850	48,070
Scenario 4b	47,900	30	47,840	47,950	47,810	47,980
Scenario 7 (Base case 3)	32,520	710	31,440	33,800	30,990	34,460
Scenario 7a	32,470	690	31,480	33,700	30,990	34,300
Scenario 7b	32,360	640	31,380	33,510	30,980	34,040

As a result of the Monte Carlo simulation, the sensitivity to the total risk is also obtained. As the result, it is found that active fire safety systems, such as smoke detection systems and sprinkler systems, are the most sensitive parameters. In particular, when a sprinkler system is presented in the building (Scenario 6 to Scenario 10), it is always the most sensitive factor.

CHAPTER 8 COST-BENEFIT ANALYSIS

8.1 Introduction to Cost-Benefit Analysis

Cost-benefit analysis is a practical way of evaluating the economic efficiency of resource allocation. By analysing the cost requirement for the risk reduction alternatives and determining the benefit cost ratio (B/C), the mutually exclusive scenarios may have a common unit so that they can be compared and ranked in accordance to their priorities. As a result, the economically best investment can be found. Overall, the information provided from the B/C analysis may include:

- The estimated equivalent monetary value of the fire risk reduction
- The initial and annual cost of the alternatives
- The B/C ratio

Any alternative scenario with a B/C ratio above one is considered to be a beneficial investment. In addition to the B/C analysis, the effectiveness and efficiency of the alternative scenarios are also discussed in this study. Since the main concern of this study is the health and safety impacts on people (life safety consequences), the benefit of the risk reduction alternatives primarily apply to the building occupants. Note that loss of property (impact on property), business interruption costs (impact on the retail shops) and environmental damage are excluded from this assessment.

In this chapter, the 14 scenarios are analysed based on three critical base scenarios. A scenario with the lowest level of fire protection (Scenario 1) is considered as the base case for Scenario 2 – Scenario 10, where a flammable liquid (mineral oil) insulated transformer is used. The purpose of this part of the analysis is to evaluate the cost and benefit of different fire safety designs without the influence of different transformer types.

Thereafter, Scenario 4 and Scenario 7 are selected as the base cases for Scenario 4a and 4b and Scenario 7a and 7b, respectively. The purpose of this part of the analysis is to evaluate the cost and benefits of different types of transformers, such as less flammable liquid (silicone oil) insulated transformers and dry type (dry air) transformers. The reason for selecting Scenario 4 and Scenario 7 as the base cases in this part is due to the fire safety designs in these two scenarios being recommended in the NFPA as mentioned in Table 3-5. Note that NFPA is the only standard provided the fire protection requirements for other types of transformers.

8.2 Methodology

According to the benefit cost analysis manual [111], the benefit cost ratio (B/C) can be measured by the total discounted benefits divided by the total discounted costs. In general, it is a beneficial investment if the B/C ratio is greater than one. The factors of the B/C ratio include:

- The existing risk estimated for the base case;
- The modified risk estimated for the alternatives;
- Initial cost of the alternatives;
- Annual cost of the alternatives;
- The present worth factor which is a function of the interest rate;
- The estimated useful lifetime of the system.

The following equations are extracted from the benefit cost analysis manual [111] to determine the B/C ratio:

Equation 8-1:

$$B/C = \frac{A(P/A, i, N)}{I_C}$$

Equation 8-2:

$$A = R_B - A_C$$

Equation 8-3:

$$R_B = R_e - R_m$$

Equation 8-4:

$$(P/A, i, N) = \frac{(1+i)^N - 1}{i \cdot (1+i)^N}$$

where

B/C	is the benefit cost ratio
A	is the cost avoidance ($)
I_C	is the initial cost ($)
A_C	is the annual cost ($)
R_B	is the risk benefit ($)
R_e	is the existing estimate risk ($)
R_m	is the modified estimate risk ($)
P/A	is the present worth factor
i	is the interest rate (%)
N	is the useful lifetime (year)

In the following section, both initial and annual costs of individual systems or equipment are provided with a distribution to capture the uncertainty in the values. However, only the mean value is used to determine the B/C ratio.

For the calculation, the annual interest rate (7%) is assumed to be constant throughout the useful lifetime of the distribution substation (30 years). The value of the annual interest rate is obtained by averaging the annual interest rate from different banks in New Zealand in 2006. As introduced by Tremblay [69], Guy [112] and ABB Power Transmission [113], an average useful lifetime of 30 years is considered to be appropriate for the major equipment in distribution substations, such as transformers and switchgear. As a result, the present worth factor (P/A, i, N) is determined to be 12.41 using Equation 8-4.

8.3 Cost Analysis for the Risk Reduction Alternatives

8.3.1 Cost Consideration

Costs of alternative scenarios can be expressed in terms of their initial costs and annual costs. In this study, initial costs are defined as the cost incurred during the first year from the system being installed, whilst annual costs are the ongoing operating costs for maintenance and rehabilitation of the system. The initial costs can be determined by the sum of two separate costs; these are:

- System (equipment) costs;
- Installation (labour) costs.

It is understood that the installation costs are very difficult to predict because it can vary significantly depending on the individual case. Rawlinsons 2004 [114] has proposed an allowance of 5% to 10% on top of the equipment costs is considered to be appropriate for the total initial costs. In addition, the cost of the individual equipment or systems are measured based on the values given in Rawlinsons 2004 [114].

On the other hand, the annual costs are the ongoing costs. These costs may include the following:

- Maintenance costs (e.g. cleaning for dry type transformers);
- Inspection and testing costs (e.g. sprinkler heads, detectors);
- Ongoing operating costs (e.g. transmission connection, on-duty observers);
- Replacement costs (e.g. oil replacements).

The cost estimates for individual equipment or systems are discussed in the following sections. Note that, smoke detection system is considered to be a common system for all scenarios; therefore, no additional costs are required from the base case. Hence, the costs estimates for the smoke detection system are not discussed in the analysis.

8.3.2 Sprinkler System

As defined previously, the model building is not protected with sprinkler systems. Therefore, if sprinkler systems are installed in a distribution substation, the total cost of the sprinkler systems should include the cost of sprinkler heads, control board, pipes, fittings, valves and the like. It is understood that in sprinklered buildings, sprinkler system is likely to be extended to the distribution substation inside and the costs of this extension is expected to be low. Therefore, the cost-effectiveness of installing a sprinkler system in the distribution substation inside a sprinklered building is expected to be higher than installing a sprinkler system in the distribution substation inside a non-sprinklered building due to its low cost. To be conservative, this research only assesses the risk of transformer fire in a non-sprinklered building. Hence, the costs of control board, valves and the like are included in the assessment.

It is understood that typical high-rise non-sprinklered buildings generally contain two individual main pipes from the main water supply: one is for the building use and another one is for fire hydrants. If sprinkler systems are installed, an additional main pipe is required for supporting the sprinkler systems separately from another two main pipe. However, through discussion with a fire service engineer [115], it is understood that the additional main pipe for the sprinkler systems may not be necessary to the model building in this assessment. It is due to the required water flow to the sprinkler heads in the distribution substation on ground floor being able to be supported by the fire hydrant pipe.

In the model building, the distribution substation is located on the ground floor of the building. The floor area is 24 m^2 with floor-to-ceiling height of 3.6 m. As mentioned, the water supply to the sprinkler heads is from another main pipe (fire hydrant). Figure 8-1 shows typical sprinkler systems and associated equipment for distribution substations. As stated in Standard NZS 4541:2003 [33], each sprinkler head can provide a coverage of 3 m by 4 m (12 m^2). However, due to the shape of the distribution substation, three sprinkler heads are required to provide a full coverage to the area. The associated equipment of the sprinkler systems includes a gate valve, a monitored valve, an inspectors connection and the Fire Service connection, as discussed by Puchovsky [116].

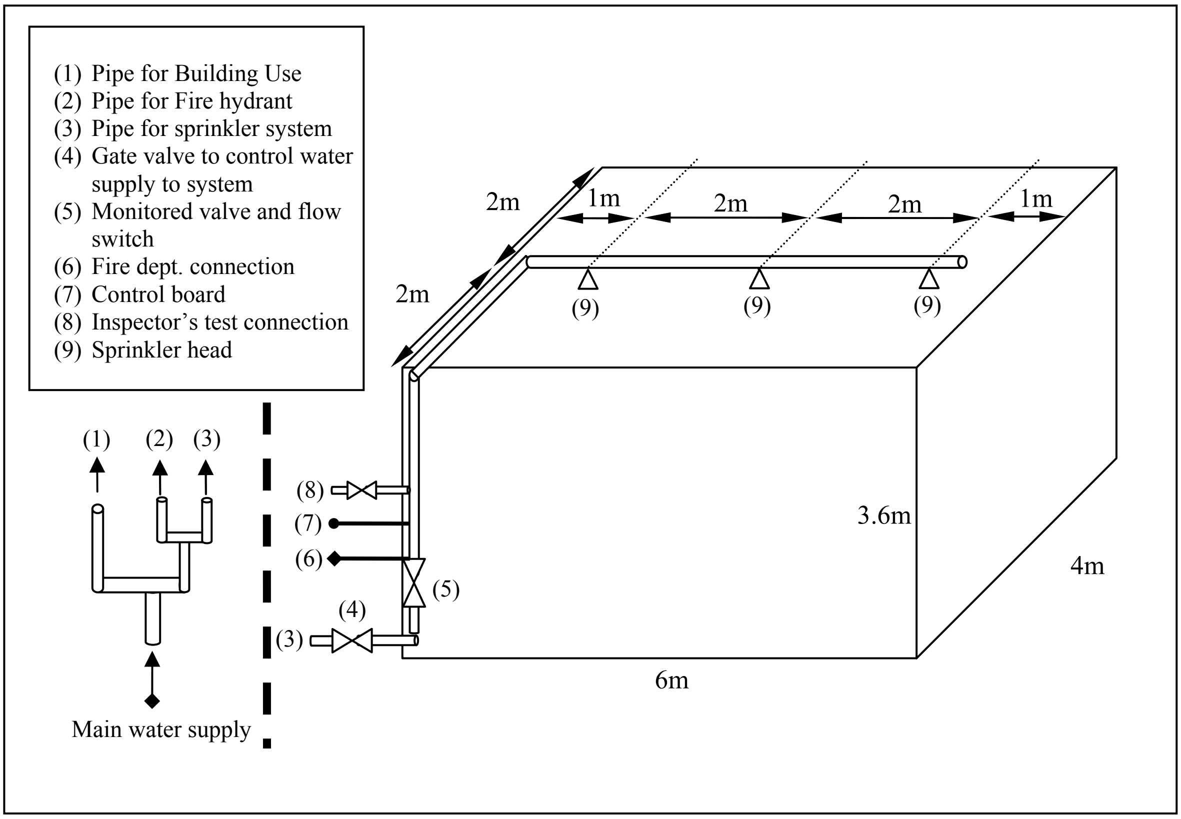


Figure 8-1: Basic components of the sprinkler systems in the distribution substation

According to Standard NZS 4541:2003 [33], the required water discharge density for liquid type and dry type transformers is at least 10 mm/min and 5 mm/min, respectively. As known, higher water discharge densities usually require larger pipe sizes, valves and fittings. Therefore, the cost of sprinkler systems for liquid type transformers is expected to be higher than the dry type transformers.

The total cost of the sprinkler systems for a distribution substation with different types of transformers, in the model building, has been evaluated by the fire service engineer [115]. Considering that the water flow and pressure of the existing fire hydrant pipe is sufficient to support the sprinkler systems (no pumps are required), a conservative total cost of the sprinkler systems are estimated to be in the range of NZD$10,000 to NZD$14,000 for distribution substations with a liquid type transformer and NZD$9,000 to NZD$13,000 for distribution substations with a dry type transformer. Note that the given costs have included the installation costs.

The frequency of the sprinkler systems inspection and testing are covered by Standard AS 1851:2005 [117]. For different parts of the system, the required inspection and testing may vary from once a year to as much as once a week. For instance, the sprinkler system interface control valves are required to be inspected weekly while the alarm valve is to be inspected yearly.

Through discussion with a senior fire protection engineer [118], the annual inspection and testing cost is estimated to be in the range of NZD$400 to NZD$600 (including weekly inspection and testing). On the other hand, the cost of the transmission connection to on-duty observer is advised to be about NZD$200 to NZD$300. In addition, the replacement cost is assumed to be in the range of NZD$0 to NZD$200 per year which may include the cost of sprinkler heads, fitting and the like. Table 8-1 shows the cost of sprinkler systems in a distribution substation and a summary of the initial costs and annual costs are indicated in Table 8-2.

Table 8-1: Cost of sprinkler systems in the distribution substation

Description		Cost (NZD$)
System/ Installation cost	Sprinkler systems for distribution substation with a liquid oil insulated transformer	$10,000 - $14,000
Inspection and testing cost	Expert engineer justified	$400 - $600 pa
On-going operation cost	Transmission connection to on-duty observer	$200 - $300 pa
Replacement cost	General equipment (e.g. sprinkler heads)	$0 - $200 pa
System/ Installation cost	Sprinkler systems for distribution substation with a dry type transformer	$9,000 - $13,000
Inspection and testing cost	Expert engineer justified	$400 - $600 pa
On-going operation cost	Transmission connection to on-duty observer	$200 - $300 pa
Replacement cost	General equipment (e.g. sprinkler heads)	$0 - $200 pa

Table 8-2: Initial costs and annual costs of sprinkler systems

Relevant scenarios	Transformer type	Initial cost (NZD$)			Annual cost (NZD$)		
		Min.	Mean	Max.	Min.	Mean	Max.
Scenario 1~5, 4a	Liquid oil type	$0	$0	$0	$0	$0	$0
Scenario 6~10, 7a	Liquid oil type	$10,000	$12,000	$14,000	$600	$850	$1,100
Scenario 4b, 7b	Dry type	$9,000	$11,000	$13,000	$600	$850	$1,100

8.3.3 Fire Resistance Rated Constructions (Wall barrier)

The cost of the FRR construction is determined based on the area of interior walls and the fire doors in the distribution substation. In this case, the total area of interior walls is determined to be 68.8m^2 (subtract the area of the fire doors). The cost of the fire walls and doors are found in Rawlinsons 2004 [114]. As mentioned previously, the labour cost is to be 5% to 10% of the equipment cost.

As expected, FRR construction has a very high reliability. According to Standard AS 1851:2005 (Table 17.4.1.1: Fire and Smoke barriers – walls) [117], fire construction is required to be inspected once every half year (e.g. check of penetrations and dampers). The maintenance, inspection and testing costs are provided by Integrity Fire Protection. An inspection cost of NZD$300 to NZD$600 is estimated. Hence, the cost of the FRR constructions and a summary of the initial costs and annual costs of the FRR construction system are shown in Table 8-3 and Table 8-4, respectively.

Table 8-3: Cost of the FRR constructions

Description			Cost (NZD$)
30 min	System cost	FRR wall: (\$128/m^2 - \$136/m^2) * 68.8m^2	$8,800 - $9,400
		Fire Door: $1,150 each (for two doors)	$2,300
	Installation cost	5% - 10% of the system costs	$560 - $1,170
	Inspection and testing cost	Expert engineer justified	$300 - $600 pa
1 hr	System cost	FRR wall: (\$132/m^2 - \$142/m^2) * 68.8m^2	$9,000 - $9,800
		Fire Door: $1,350 each (for two doors)	$2,700
	Installation cost	5% - 10% of the system costs	$590 - $1,250
	Inspection and testing cost	Expert engineer justified	$300 - $600 pa
2 hr	System cost	FRR wall: (\$157/m^2 - \$170/m^2) * 68.8m^2	$10,000 - $11,700
		Fire Door: $1,500 each (for two doors)	$3,000
	Installation cost	5% - 10% of the system costs	$590 - $1,470
	Inspection and testing cost	Expert engineer justified	$300 - $600 pa

Table 8-3 continued

Description			Cost (NZD$)
3 hr	System cost	FRR wall: ($159/m^2 - $168/m^2) * 68.8m^2	$10,900 - $11,700
		Fire Door: $1,750 each (for two doors)	$3,500
	Installation cost	5% - 10% of the system costs	$720 - $1,520
	Inspection and testing cost	Expert engineer justified	$300 - $600 pa
4 hr	System cost	FRR wall : ($173/m^2 - $205/m^2) * 68.8m^2	$11,900 - $ 14,100
		Fire Door : $2,100 each (for two doors)	$4,200
	Installation cost	5% - 10% of the system costs	$805 - $1,830
	Inspection and testing cost	Expert engineer justified	$300 - $600 pa

Table 8-4: Initial costs and annual costs of the FRR construction

Relevant scenarios	Description	Initial cost (NZD$)			Annual cost (NZD$)		
		Min.	Mean	Max.	Min.	Mean	Max.
Scenario 1, 6	30 minute FRR: total FRR wall area = 68.8m^2, two single doors	$11,700	$12,300	$12,900	$300	$450	$600
Scenario 2, 7, 7a, 7b	1 hour FRR: total FRR wall area = 68.8m^2, two single doors	$12,300	$13,100	$13,800	$300	$450	$600
Scenario 3, 8	2 hour FRR: total FRR wall area = 68.8m^2, two single doors	$13,700	$15,400	$16,200	$300	$450	$600
Scenario 4, 9, 4a, 4b	3 hour FRR: total FRR wall area = 68.8m^2, two single doors	$15,100	$16,000	$16,700	$300	$450	$600
Scenario 5, 10	4 hour FRR: total FRR wall area = 68.8m^2, two single doors	$16,900	$18,900	$20,100	$300	$450	$600

8.3.4 Type of Transformer

Three types of transformers are evaluated in this research. These include:

- Flammable liquid insulated transformer (mineral oil)
- Less flammable liquid insulated transformer (silicone oil)
- Dry type transformer (dry air)

A mineral oil insulated transformer is chosen as the base transformer type for the assessment. Through discussion with a senior sales engineer [97], the cost of a mineral oil insulated transformer is estimated about NZD$26,000 to NZD$28,000. The cost relationship between other types of transformer and the mineral oil insulated transformer is found in Goudie [56]. Taking the cost of a mineral oil insulated transformer as 100%, the relative initial costs of silicone oil insulated transformers and dry type transformers are found to be between 125% to 135% and between 130% to 200%, respectively (including the initial cost of the dielectric fluid). Therefore, the cost of a silicone oil insulated transformer and a dry type transformer are determined to be in the range of NZD$32,500 to NZD$37,800 and NZD$33,800 to NZD$56,000, respectively, as shown in Table 8-5.

The Hydroelectric Research and Technical Services Group [119] states that transformer oil rehabilitation should take place at the 10-year point and so on until the end of the useful lifetime of the transformer (approximately 30 years). Therefore, it is assumed the entire volume of transformer oil is replaced once every 10 years. In the recent market, the cost of mineral oil and silicone oil is found to be NZD$15 to NZD$30 and NZD$12 to NZD$15 per litre, respectively. Hence, for a transformer containing about 550L to 840L of oil, the cost of oil retrofill is estimated to be NZD$8,250 to NZD$25,200 (mineral oil) and NZD$6,600 to NZD$12,600 (silicone oil). Assuming the retrofill cost is equally split into 10 years, the replacement cost is estimated to be about NZD$825 to NZD$2520 (mineral oil) and NZD$660 to NZD$1,260 (silicone oil) per year.

For the inspection and testing cost, the senior sales engineer [97] suggested that the annual maintenance cost of liquid type transformers is to be at least twice that of the dry type transformers. Note that the maintenance cost relationship between liquid type and dry type transformers recommended is in disagreement with the reference by Goudie and Chatterton [56] as indicated in Section 4.7.1. It is because the testing cost of the dielectric materials are excluded in Goudie and Chatterton [56]. Therefore, the maintenance cost relationship proposed by the senior sales engineer [97] is used in the assessment. As advised, the maintenance cost of liquid type transformers is about NZD$400 to NZD$600 per year. Therefore, the maintenance cost of dry type transformers is estimated to be NZD$200 to NZD$300 per year. Note that replacement costs of a dry type transformer are likely to be low and is generally included in the inspection and testing costs. Therefore, it is neglected in the assessment. A summary of the initial costs and annual costs of different types of transformers are shown in Table 8-6.

Table 8-5: Cost of different types of transformer

Description		Cost (NZD$)
System/ Installation cost	Flammable liquid insulated transformer (mineral oil)	$26,000 - $28,000
Inspection and testing cost	Expert engineer justified	$400 - $600 pa
Replacement cost	Replace once in 10 years. Oil costs $15 - $30 per liter with a total of 550L - 840L oil	$830 - $2,520 pa
System/ Installation cost	Less flammable liquid insulated transformer (Silicone oil): 25%~35% above the cost of a mineral oil insulated transformer	$32,500 - $37,800
Inspection and testing cost	Expert engineer justified	$400 - $600 pa
Replacement cost	Replace once in 10 years. Oil costs $12 - $15 per liter with a total of 550L - 840L oil	$660 - $1,260 pa
System/ Installation cost	Dry type transformer (Dry air): 30%~100% above the cost of a mineral oil insulated transformer	$33,800 - $56,000
Inspection and testing cost	Expert engineer justified	$200 - $300 pa
Replacement cost	Very low and is included in the inspection and testing cost	Neglect

Table 8-6: Initial costs and annual costs of different types of transformers

Relevant scenarios	Description	Initial cost (NZD$)			Annual cost (NZD$)		
		Min.	Mean	Max.	Min.	Mean	Max.
Scenario 1 – 10	Liquid type (Mineral oil)	$26,000	$27,000	$28,000	$1,230	$1,990	$3,120
Scenario 4a, 7a	Liquid type (Silicone oil)	$32,500	$35,200	$37,800	$1,060	$1,400	$1,860
Scenario 4b, 7b	Dry type (Dry air)	$33,800	$44,900	$56,000	$200	$250	$300

8.3.5 Summary of the Cost Estimate

A summary of the initial costs and annual costs for each scenario is shown in Table 8-7.

Table 8-7: Summary of initial costs and annual costs (Mean value only)

	Sprinkler system		FRR construction		Transformer type		Total cost	
	I_C (NZD$)	A_c (NZD$)	I_C (NZD$)	A_c (NZD$)	I_C (NZD$)	A_c (NZD$)	I_C (NZD$)	A_c (NZD$)
Scenario 1 (Base case 1)	$0	$0	$12,330	$450	$27,000	$1,990	$39,330	$2,440
Scenario 2	$0	$0	$13,140	$450	$27,000	$1,990	$40,140	$2,440
Scenario 3	$0	$0	$15,440	$450	$27,000	$1,990	$42,440	$2,440
Scenario 4	$0	$0	$15,980	$450	$27,000	$1,990	$42,980	$2,440
Scenario 5	$0	$0	$18,640	$450	$27,000	$1,990	$45,640	$2,440
Scenario 6	$12,000	$800	$12,330	$450	$27,000	$1,990	$51,330	$3,240
Scenario 7	$12,000	$800	$13,140	$450	$27,000	$1,990	$52,140	$3,240
Scenario 8	$12,000	$800	$15,440	$450	$27,000	$1,990	$54,440	$3,240
Scenario 9	$12,000	$800	$15,980	$450	$27,000	$1,990	$54,980	$3,240
Scenario 10	$12,000	$800	$18,640	$450	$27,000	$1,990	$57,640	$3,240
Scenario 4 (Base case 2)	$0	$0	$15,980	$450	$27,000	$1,990	$42,980	$2,440
Scenario 4a	$0	$0	$15,980	$450	$35,100	$1,390	$51,080	$1,840
Scenario 4b	$0	$0	$15,980	$450	$44,550	$250	$60,530	$700
Scenario 7 (Base case 3)	$12,000	$800	$13,140	$450	$27,000	$1,990	$52,140	$3,240
Scenario 7a	$12,000	$800	$13,140	$450	$35,100	$1,390	$60,240	$2,640
Scenario 7b	$11,000	$800	$13,140	$450	$44,550	$250	$68,690	$1,500

Note: I_c is the initial costs and A_c is the annual costs

8.4 Risk Reduction Benefit Cost Ratio

According to Barry [93], Cost Benefit ratio (B/C) can be determined using Equation 8-1. Given the present worth factor (P/A, i, N) of 12.41, the equation of benefit cost ratio can be rewritten by substituting Equation 8-2 and Equation 8-3, as follows:

Equation 8-5: $$B/C = \frac{12.41 \cdot (R_e - R_m - A_C)}{I_C}$$

Based on the estimated total risk in Section 7.8 and the initial and annual costs in Section 8.3.5, the B/C ratio for the risk reduction strategies are determined using Equation 8-5. Note that the estimated total risk of the base case is considered as the existing risk (R_e) while the estimated total risk of the alternatives is the modified risk (R_m). In the B/C ratio calculation, the initial costs (I_C) and annual costs (A_C) of the alternatives are determined based on the cost difference from its respective base case.

For scenarios being a base case, no B/C ratio is expected since no risk benefit is expected. A summary of the results of the B/C ratio calculation is indicated in Table 8-8 (Also refer to Appendix F). In addition, the ranking of the B/C ratio of the alternatives are listed systematically in Table 8-9 through Table 8-11.

Table 8-8: A summary of the results of the B/C ratio calculation

	[1] Existing risk, R_e (NZD$) [1] Modified risk, R_m (NZD$)	[2] Risk benefit R_B (NZD$)	[3] Initial costs I_C (NZD$)	[3] Annual costs A_C (NZD$)	B/C ratio
Scenario 1 (Base case 1)	49,690	$0			N/A
Scenario 2	49,690	$0	$810	$0	0.0
Scenario 3	49,330	$360	$3,110	$0	1.4
Scenario 4	48,620	$1,080	$3,650	$0	3.7
Scenario 5	47,990	$1,700	$6,310	$0	3.4
Scenario 6	32,520	$17,180	$12,000	$850	16.9
Scenario 7	32,520	$17,180	$12,810	$850	15.8
Scenario 8	32,490	$17,210	$15,110	$850	13.4
Scenario 9	32,420	$17,270	$15,650	$850	13.0
Scenario 10	32,370	$17,320	$18,310	$850	11.2
Scenario 4 (Base case 2)	48,620	$0	$0	$0	N/A
Scenario 4a	47,960	$650	$8,100	($560)	1.9
Scenario 4b	47,900	$720	$17,550	($1,740)	1.7
Scenario 7 (Base case 3)	32,520	$0	$0	$0	N/A
Scenario 7a	32,470	$50	$8,100	($600)	1.0
Scenario 7b	32,360	$150	$16,550	($1,740)	1.4

[1] Note that the estimated total risk of the base case is the existing risk, R_e, and the estimated total risk of the alternatives is the modified risk, R_m.

[2] Risk benefit is the difference between the existing risk, R_e and the modified risk, R_m.

[3] Initial costs, I_C, and annual costs, A_C, in the table indicate the cost difference from its respective base case; hence, when the required costs of alternatives are less then the costs of its respective base case, negative costs may result (as shown in the brackets).

* N/A – Not applicable

Table 8-9: Ranking of the B/C ratios with Scenario 1 as the base case

Rank	B/C ratio	Scenario	Smoke detection system	Sprinkler system	FRR construction	Transformer type
-----	N/A	Scenario 1	Yes	No	30 minute	Mineral oil insulated transformer
1	16.9	Scenario 6	Yes	Yes	30 minute	Mineral oil insulated transformer
2	15.8	Scenario 7	Yes	Yes	1 hour	Mineral oil insulated transformer
3	13.4	Scenario 8	Yes	Yes	2 hour	Mineral oil insulated transformer
4	13.0	Scenario 9	Yes	Yes	3 hour	Mineral oil insulated transformer
5	11.2	Scenario 10	Yes	Yes	4 hour	Mineral oil insulated transformer
6	3.7	Scenario 4	Yes	No	3 hour	Mineral oil insulated transformer
7	3.4	Scenario 5	Yes	No	4 hour	Mineral oil insulated transformer
8	1.4	Scenario 3	Yes	No	2 hour	Mineral oil insulated transformer
9	0.0	Scenario 2	Yes	No	1 hour	Mineral oil insulated transformer

* N/A – Not applicable

Table 8-10: Ranking of the B/C ratios with Scenario 4 as the base case

Rank	B/C ratio	Scenario	Smoke detection system	Sprinkler system	FRR construction	Transformer type
-----	N/A	Scenario 4	Yes	No	3 hour	Mineral oil insulated transformer
1	1.9	Scenario 4a	Yes	No	3 hour	Silicone oil insulated transformer
2	1.7	Scenario 4b	Yes	No	3 hour	Dry type transformer

* N/A – Not applicable

Table 8-11: Ranking of the B/C ratios with Scenario 7 as the base case

Rank	B/C ratio	Scenario	Smoke detection system	Sprinkler system	FRR construction	Transformer type
-----	N/A	Scenario 7	Yes	Yes	1 hour	Mineral oil insulated transformer
1	1.0	Scenario 7b	Yes	Yes	1 hour	Dry type transformer
2	1.4	Scenario 7a	Yes	Yes	1 hour	Silicone oil insulated transformer

* N/A – Not applicable

8.5 Discussion

Overall, it is found that scenarios with a sprinkler system, such as Scenario 6 to Scenario 10, would generally have higher C/B ratio than scenarios with no sprinkler protection, such as Scenario 1 to Scenario 5. As the results of the B/C analysis, Scenario 6 is found to be the economically best option and followed by scenarios having a higher FRR construction.

In scenarios with sprinkler protection, it is found that the higher FRR construction would have the lower the B/C ratio, (The B/C ratio is reduced from 16.9 for Scenario 6 (FRR of 30 minutes) to 11.2 for Scenario 10 (FRR of 4 hours). In scenarios without sprinkler protection, the scenario with a 3 hour FRR construction (Scenario 4) is considered to be the most cost-effective solution in terms of occupants' life safety consequence.

In general, the results of the assessment agree with most of the regulation standards and the non-regulation guidelines as studied in the literature review section. The fire safety design options required by the standards and guidelines in Section 1.1 with respect to the corresponding B/C ratio determined are indicated in Table 8-12.

Table 8-12: The ranking for the fire safety design options required in the standards and guidelines

Option	C/AS 1	NZFS	NFPA	BCA	IEEE	FM Global	Electricity provider (1)	Electricity provider (2)
1	9th	7th	6th	N/A	N/A	6th	8th	8th
2	N/A	N/A.	2nd	3rd	N/A.	2nd	N/A	2nd

* N/A = Not applicable

It should be noted that the analysis consists of a certain amount of uncertainty, such as the cost of sprinkler systems and inspections are evaluated based only on engineering judgement. These costs may be different from one case to another.

As known, a B/C ratio of greater than one implies the scenario is a beneficial investment whilst a B/C ratio less than one implies it is a loss investment. In this case, the B/C ratio for all scenarios is well above the critical value of one. This result not only shows that all alternative scenarios are beneficial investments, it also indicates that the alternative scenarios are very cost-effective. The total risk for the first ten scenarios and their corresponding B/C ratio are shown in Figure 8-2.

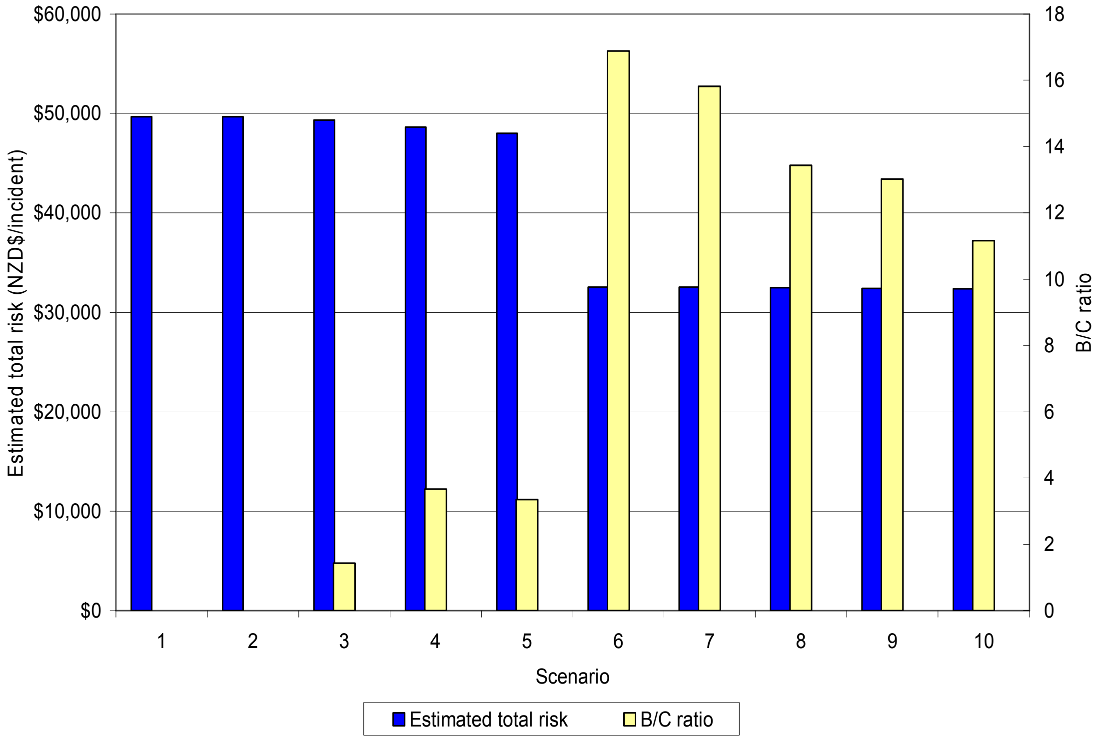


Figure 8-2: Estimated total risk of the alternatives and their corresponding B/C ratio

As can be seen, the total risk for the scenarios containing sprinkler systems, i.e. Scenario 6 to Scenario 10, is relatively low (The EMV is about NZD$30,000) compared to the scenarios without sprinkler systems, Scenario 1 to Scenario 5 (The EMV is about NZD$50,000). It should be noted that in the case of a sprinklered building, where the cost of extending the sprinkler system to the distribution substation is considered to be low compared to a non-sprinklered building. It may result a higher B/C ratio for scenarios with sprinkler system due to the reduced cost. Further study may be required to carry on the comparison between the buildings with and without sprinkler protection.

In the event of mineral oil insulated transformer fire in a distribution substation, large amounts of fuel is expected in the room due to the presence of oil. In such cases, if sprinkler systems are not installed, such as Scenario 1 to Scenario 5, low FRR construction is not considered to be sufficient to confine the fire. This concept is in agreement with the results of the B/C analysis, where Scenario 2 (1 hour FRR and no sprinkler system) and Scenario 3 (2 hour FRR and no sprinkler system) are both ranked near the bottom among the 9 alternatives. On the other hand, if sprinkler systems are installed, such as Scenario 6 to Scenario 10, according to the results of the B/C analysis, a construction having a FRR of 30 minute (Scenario 6) is considered to be the most cost-effective solution.

In the second part of the B/C analysis, two other types of transformers replacing the flammable liquid (mineral oil) insulated transformer in a distribution substation are assessed. These are the less flammable liquid insulated (silicone oil) transformer and the dry type (dry air) transformer. As the results of the B/C analysis indicate, both these transformers are considered as a beneficial investment. This meant that replacing an existing mineral oil insulated transformer with a silicone oil or dry air insulated transformer is considered to be cost effective based on the B/C analysis presented in this report.

It was found that the B/C ratio of less flammable liquid insulated transformers can be higher or lower than the B/C ratio of the dry type transformers depending on the existing fire safety design of the distribution substation. In the case of Scenario 4, as the base case, the scenario with the less flammable liquid insulated transformer has a higher B/C ratio. This result is considered to be reasonable since the dry type transformers are known as low hazard equipment and, thus, 3 hour FRR construction seems to be redundant. On the other hand, in the case of Scenario 7, as the base case, the scenario with the dry type transformer has a higher B/C ratio.

Overall, it is found that using sprinkler system or replacing transformers with lower hazard in distribution substation can sufficiently reduce the fire risk to occupants in a high-rise building.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from this analysis:

- Fire safety design requirements for distribution substations are obtained from different standards and guidelines. However, the requirements in these documents are inconsistent. For a distribution substation containing a flammable liquid insulated transformer with no sprinkler system installed, the recommended fire separation constructions vary between 1 hour FRR and 4 hour FRR. When sprinkler systems are installed, the fire separation can generally reduce to 2 hour FRR or lower. Moreover, only one standard and one guideline provided the fire safety design of distribution substation containing less flammable liquid insulated transformers. As recommended, fire separation construction having a FRR of 1 hour or 3 hour is required in a non-sprinklered distribution substation. When sprinkler systems are installed, no FRR constructions are required. Typically, a dry type transformer does not carry any a high hazard materials, hence, no fire separation constructions are required.

- According to data provided by the NZFS FIRS [65], there were a total of 20 structure fires originating in distribution substations, in typical New Zealand buildings, during the 6 year period from January 2000 to January 2006. There were 13 fire incidents involving faults in the electrical wire and wiring insulation, and 4 fire incident having transformer and transformer fluid as the object first ignited. No fatalities were recorded for these fire incidents. In addition, it is found that the total number of distribution substations in New Zealand increased from about 24,000 in 1946 to about 170,000 in 2006.

- The number of structure fires originating in switchgear areas or transformer vaults (distribution substation) and their consequences are obtained from the NFIRS. During the 22 year period from 1980 to 2002, an average of 1251 fires, 71 civilian injuries and 3 civilian deaths were recorded each year.

- The reliability of transformers and fire protection systems were studied in this research. Typical failure rates for transformers (fires may or may not occur) are found to be in the range of 0.2 x 10^{-3} to 140 x 10^{-3} failures per year. The reliability of smoke detection systems and sprinkler systems for general buildings were found to be in the range of 77.8% to 94% and 81.3% to 99.5%, respectively.

- The statistical data used in this research may contain uncertainties due to the lack of information on the specified data for the fire safety protection systems, such as the reliability of smoke detection systems and sprinkler systems in distribution substation. Hence, further studies may be required for obtaining a more accurate result.

- As a result of the Event Tree Analysis, the overall risks are obtained for a total of 14 scenarios. The probability of the various consequences is calculated by multiplying the various branch probabilities of each factor and the consequences are determined based on the rates of civilian causalities in a fire and the value of statistical life (VSL). From literature, the value of statistical life is found to be \$3 million for a death and \$250,000 for an injury. As the result of the ETA analysis, Scenario 1, which contains the lowest level of fire safety design compared to the other scenarios, has the highest total risk, NZD\$49,690 per transformer fire incident in a substation. As the level of fire safety increases, the total risk is expected to be reduced. Using the same type of transformer (Scenario 1 to Scenario 10), Scenario 10, which contains the highest level of fire safety design compared to the other scenarios, has reduced the total risk to NZD\$32,370 per transformer fire incident in a substation.

- From the Cost-Benefit Analysis, it is found that construction having a FRR of 4 hour and no sprinkler system installed, as proposed by the NZFS, is not considered to be the economically best option. As the result of the C/B ratio ranking, it is found that scenarios with a sprinkler system (Scenario 6 to Scenario 10) would generally have more cost benefit than scenarios without sprinkler system (Scenario 2 to scenario 5). Out of the nine scenarios having the same transformer type, Scenario 6 (sprinkler system provided/ 30 minutes FRR construction) is found to be the most cost effective scenario with a B/C ratio of 16.9. Moreover, in a non- sprinklered building, a scenario with 3 hours FRR construction (Scenario 4) is found to have the highest B/C ratio (3.7). Note that the cost-benefit analysis in this research does not concern the property damage, business continuity or environment damage caused by transformer fires or fire extinguishments.

As a result of this study, the following recommendations are offered:

- The proposed four hour fire separation between the distribution substations and the interior spaces of the building, when no sprinkler system is provided, is not considered to be the most cost-effective alternative to the life safety of the building occupants.

- From the life safety perspective, distribution substation in a high rise building is recommended to be protected by sprinklers and smoke detectors. If sprinkler system is provided, the FRR construction of the substation could be reduced to 30 minutes. If sprinkler system is not provided, construction may be required to have a higher FRR. As the result of the analysis, 3 hour FRR construction is determined to have the highest cost-benefit ratio in a non-sprinklered building.

- In addition, replacing a flammable liquid insulated transformer with a less flammable liquid insulated transformer or a dry type transformer is generally considered to be economical alternatives.

Future research is recommended in the following areas:

- The 20 fire incidents in distribution substations, used in the report are not considered to be sufficient and representative. Further statistical analysis of indoor transformer fire incidents is recommended in order to obtain a more accurate result.

- Conduct more detailed modeling to predict the environment conditions, the effect of toxic substances and effect of fires and explosions on building occupants.

- Explosion hazards are one of the main concerns in the event of a transformer fire. Further studies may be required in this particular area.

- In addition to the occupant life safety as evaluated in this research, Clauses C1 – C4 of the NZBC also requires the prevention of fire spread to adjacent properties and the protection of fire service personnel during fire rescue operations. To provide a complete assessment and recommendations on the fire protection for indoor distribution substation in residential buildings, further studies on these aspects is needed.

REFERENCES

1. Nyman, J., *Private communication*. 2005: New Zealand.
2. Shortreed, J.H., L. Craig, and S. McColl, *Benchmark Framework for Risk Management.* Network for Environmental Risk Assessment and Management, Aug 2000.
3. Department of Building and Housing, *Compliance Document for New Zealand Building Code Clauses C1, C2, C3, C4 Fire Safety*. 2005, Department of Building and Housing.
4. Transpower NZ Ltd., *Annual Report 04/05: The National Grid*. 2004/05.
5. Tizard, C.A., M.H. Boy, and S. Cartwright, *The Building Regulations 1992 and subsequent amendments*. Jun 1992, Authority of the New Zealand Government.
6. Contact Energy Ltd., *Power*. 2001: http://www.contactenergy.co.nz/power.htm.
7. Genesis Energy Ltd., *Delivering responsible energy solutions*. 2003: http://www.genesisenergy.co.nz/genesis/generation/how-we-generate-your-power/en/how-energy-is-generated_home.cfm#.
8. Meridian Energy Ltd., *Electricity generation in New Zealand,* http://www.meridianenergy.co.nz/aboutus/education/default.htm.
9. Lin, W.H., *Analysis of fire detection and suppression system for outdoor oil-filled transformers*, in *Fire Protection Engineering*. 1991, Worcester Polytechnic Institute: Worcester MA, USA.
10. Gibbs, J.B., *Transformer principles and practice*. 1st Ed, 8th impression ed. 1937, New York: McGraw-Hill. ix, 210.
11. Myers, S.D., J.J. Kelly, and R.H. Parrish, *A guide to transformer maintenance*. 1981, Akron, Ohio: Transformer Maintenance Institute. xix, 836.
12. Heathcote, M.J. and D.P. Franklin, *The J & P transformer book : a practical technology of the power transformer*. 12th ed. 1998, Oxford ; Boston: Newnes. xiv, 945.
13. Zalosh, R.G., *Industrial fire protection engineering*. 2003, New York: Wiley.
14. Connelly, F.C., *Transformers: their principles and design for light electrical engineers*. 1965, London, UK: SIR ISAAC PITMAN & SONS Ltd.

15. Blume, L.F., *Transformer engineering: a treatise on the theory, operation, and application of transformers*. 2nd ed. General electric series. 1951, New York: Wiley. ix, 500.
16. Bean, R.L., et al., *Transformers for the electric power industry*. 1959, New York, Toronto, London: McGraw-Hill.
17. Mathews, P., *Protective current transformer and circuits*. 1955, London: Chapman & Hall.
18. Josken, J. and D. Wareham, *Seed based oil as an alternative to mineral oil.* IEEE Xplore, May 2004.
19. Oommen, T.V., *Vegetable oils for liquid-filled transformers*. IEEE Xplore, Jan/Feb 2002. **Vol. 18**(1): p. 6-11.
20. Hallerberg, D.A., *Less-flammable liquids used in transformers*. IEEE Xplore, Jan/Feb 1999. **Vol. 5**(1): p. 50-55.
21. Mcshane, C.P., *Vegetable-oil-based dielectric coolants*. IEEE Xplore, May/Jun 2002. **Vol. 8**(3): p. 34 - 41.
22. Goldman, E., *Wanted: Cleans Up PCBs, No O2 Required*. July 2006 (http://www.mdsg.umd.edu/CQ/V05N1/side1.html).
23. Bracco, R.D., *Reducing the risk of death and injuries to firefighters and citizens from electrical substation incidents in San Francisco*, ed. San Francisco Fire Department. Jan 1996: Emmitsburg, MD.
24. FM Global Technologies, *Approval standard for Less Flammable Transformer Fluids*. Aug 1993, Factory Mutual Insurance Company.
25. McCormick, G.P. and E. Howells, *Arcing resistance of high fire point dielectric liquids*. IEEE Xplore, 1997. **Vol. 12**(3): p. 1184-1192.
26. Toda, K., *Structural features of gas insulated transformers*. IEEE Xplore, 2002. **Vol. 1**: p. 508-510.
27. Gajic, Z., et al., *Sensitive Turn-to-Turn Fault Protection for Power Transformers*, in *ABB Ltd.* 2004.
28. Hattangadi, A.A., *Electrical fires and failures: a prevention and troubleshooting guide*. 2000, New York: McGraw-Hill. xviii, 281.
29. Bartley, W.H., *Analysis of Transformer Failures*, in *International Association of Engineering Insurers 36th Annual Conference*. 2003, The Hartford Steam Boilder Inspection & Insurance Co.: Stockholm, Sweden.

30. Moss, T.R., *The reliability data handbook*. 2005, London: Professional Engineering. xix, 287.
31. Vector Ltd., *Fire protection Guidelines for Distribution Substations*. May 1997(1).
32. Buchanan, A.H., Structural Engineering Society New Zealand, and New Zealand Fire Protection Association, *Fire Engineering Design Guide*. 2nd ed. 2001, Christchurch, N.Z.: Centre for Advanced Engineering. x, 240.
33. Standards New Zealand, *NZS 4541:2003 - Fire Sprinkler Systems standard*. 2003.
34. NFPA 70, *National Electrical Code*. Vol. 4. 2005: National Fire Protection Association. p.70-321 ~ p.70-328.
35. NFPA 220, *Standard on Types of Building Construction* Vol. 7. 2005: National Fire Protection Association. p.220-6.
36. NFPA 850, *Recommended Practice for Fire protection for Electric Generating Plants and High Voltage Direct Current Converter Stations*. Vol. 15. 2005: National Fire Protection Association. p.850-11 ~ p.850-12.
37. NFPA 30, *Flammable and Combustible Liquids Code*. Vol. 3. 2005: National Fire Protection Association. p.30-12.
38. The Hazardous Waste (Wales) Regulations 2005, *Statutory Instrument 2005 - No. 1806 (W.138): Environmental Protection.* http://faolex.fao.org/docs/html/uk61123.htm, July 2005.
39. NFPA 13, *Standard for the Installation of Sprinkler systems* Vol. 2. 2005: National Fire Protection Association. p.13-20, p.13-181.
40. NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection* Vol. 2. 2005: National Fire Protection Association.
41. NFPA 25, *Standard for the Inspection, Testing and Maintenance of Water-Bases Fire Protection System*. Vol. 2. 2005: National Fire Protection Association.
42. IEEE, *IEEE Guide for Substation Fire Protection*. 1995, New York, US: Institute of Electrical and Electronics Engineers.
43. Nyman, J., *Equivalent Fire Resistance Ratings of Construction Elements Exposed to realistic Fires*, in *Civil Engineering* 2002, University of Canterbury: Christchurch, New Zealand.
44. Proulx, G. and R. Fahy, *Time delay to start evacuation: Review of five case study*. Fire safety Science; Proceedings of the 5th International Symposium, 1997: p. 783-794.
45. Proulx, G., *Evacuation time and movement in apartment buildings*. Fire safety Journal, 1997. **24**: p. 229-246.

46. Brennan, P., *Timing Human Response in real fires.* Fire safety Science, Proceedings of the 5th International Symposium, 1997: p. 807-818.
47. Victoria University of Technology, *VUT assessment: Review of 14 case study.* February 2000.
48. Proulx, G., *Movemoent of people: The evacuation timing,.* SFPE Handbook of Fire Protection Engineering 3rd Ed. Section 3 Chapter 13,.
49. Fitzgerald, E., et al., *Health effects three years after potential exposure to the toxic contaminants of an electrical transformer fire.* Archives of environmental health, Jul 1989. **Vol. 44**(4): p. 214 - 221.
50. Eschenroeder, A. and E. Faeder, *Monte Carlo analysis of health risks from PCB-contaminated mineral oil transformer fires.* Risk Analysis, Jun 1988. **8**(2): p. 291- 297.
51. Heskestad, G. and P.H. Dobson, *Pool Fires of Transformer Oil Sinking into a Rock Bed.* Fire Safety Journal, 1997. **Vol. 28**: p. 33-46.
52. Bartley, W.H., *Analysis of Transformer Failures – A Twenty Year Trend*, T.H.S.B.I.I. Co., Editor. 2000, The Hartford Steam Boilder Inspection & Insurance Co.
53. Bartley, W.H., *Life Cycle management of Utility transformer Assets*, in *Breakthrough Asset Management for the Restructured Power Industry*. 2002, The Hartford Steam Boilder Inspection & Insurance Co.: Salt Lake City, Utah.
54. Bartley, W.H., *Investigating Transformer Failures* 2003, The Hartford Steam Boilder Inspection & Insurance Co.
55. Bartley, W.H. and R. James, *Transformer Asset Management* 2003, The Hartford Steam Boilder Inspection & Insurance Co. & Entergy Corporation.
56. Goudie, J.L. and W.J. Chatterton, *Environmental and life cycle considerations for distribution and small power transformer selection and specification.* IEEE Xplore, Apr 2002.
57. Babrauskas, V. and S.J. Grayson, *Heat release in fires.* 1992, London ; New York: Elsevier Applied Science. xii, 644.
58. Bertrand, Y. and L.C. Hoang, *Vegetal oils as substitute for mineral oils.* IEEE Xplore, 2003. **Vol. 2**: p. 491 - 494.
59. ASTM: D 4652-92, *Annual book of ASTM standards: Standard specification for Silicone fluid used for electrical insulation.* Vol. 10.03. 2002, West Conshohocken, PA: ASTM International.

60. ASTM: D 3487-00, *Annual book of ASTM standards: standard specification for Mineral Insulation Oil used in electrical apparatus*. Vol. 10.03. 2002, West Conshohocken, PA: ASTM International.

61. ASTM: D 2283-86, *Annual book of ASTM standards: standard specification for Chlorinated Aromatic Hydrocarbons (Askarels) for transformers*. Vol. 10.03. 2002, West Conshohocken, PA: ASTM International.

62. Trabulus, S., *Design criteria for SF6 gas insulated power transformers up to 2500 kVA.* IEEE Xplore, 1999. **vol.1**: p. 321 - 326.

63. Patel, D., *Dry Type Transormers: The better alternative to liquid filled.* Electricity Today, 2004(2).

64. New Zealand Fire Service, *New Zealand Fire Service Fire Incident Reporting System Instruction & Coding Manual: For data collected after 1 July 1995*, ed. P.a.R.D.N. Headquartes. 1995, Weillington, NZ.

65. New Zealand Fire Service, *Fire Investigation reports*. 2000 - 2006, Wellington.

66. Ahrens, M. and E.R. Twomey, *Structure fire originating in switchgear areas or transformer vaults by year 1980 - 2002.* Fire Analysis and Research Division, NFPA, Apr 2006.

67. Ragusa, L.J., *Transformer fire.* WNYF, 1984. **Vol. 45**(4): p. 16-18.

68. Courtney, N., *Transformer fire injures four: California.* Fire Journal, Jul/ Aug 1988. **Vol. 82**(4): p. 16.

69. Tremblay, K.J., *Smoke from elevator transformer fire fills hospital: Massachusetts.* NFPA Journal, Sep/ Oct 1996. **Vol. 90**(5): p. 26.

70. New Zealand. Energy and Resources Division. and Market Information and Analysis Group., *Annual statistics in relation to electric power industry in New Zealand : for the year ended 31 March.* Vol. 1989-1993. 1989, Wellington, N.Z.: Energy and Resources Division Ministry of Commerce. 5 v.

71. New Zealand. Energy Modelling and Statistics Unit., *Energy data file*, Wellington, N.Z.: Energy Policy Energy and Resources Division Ministry of Commerce. v.

72. New Zealand. Energy Modelling and Statistics Unit., *New Zealand electricity enterprise statistics: for the year ended 31 March.* Vol. 1994-1995. 1995, Wellington, N.Z.: Energy Modelling and Statistics. Unit Energy Policy Group Energy and Resources Division Ministry of Commerce. v.

73. New Zealand. Ministry of Energy. , Market Information and Analysis Group., and New Zealand Electricity., *Annual statistics in relation to electric power development*

and operation year ended, 31 March. Vol. 1958-1988. 1959, Wellington, N.Z.: Electricity Dept. v.

74. Boykin, R.F., M. Kazaians, and R.A. Freeman, *Comparative fire risk study of PCB transformer*. Risk Analysis, Sep 1985. **Vol. 6**(4).
75. x-rates.com, *New Zealand Dollars to 1 USD (Based on Federal Reserve Bank of New York)*. 1995 - 2007, http://www.x-rates.com/d/NZD/USD/hist2006.html.
76. Green, A.E., *Safety systems reliability*. 1983, Chichester: Wiley. xi,293.
77. American Institute of Chemical Engineers. Center for Chemical Process Safety., *Guidelines for process equipment reliability data with data tables*. 1989, New York, N.Y.: Center for Chemical Process Safety of the American Institute of Chemical Engineers. xix, 303.
78. Bukowski, R.W., E.K. Budnick, and C.F. Schemel, *Estimates of the Operational Reliability of Fire Protection Systems*. 1999: National Institute of Standards and Technology.
79. Yung, D., et al., *FiRECAM Version 1.6.1 - Expert Tools and Options Manual*. Apr 2006, Canada: National Research Council of Canada NRCC.
80. Thomas, I.R., *Effectiveness of Fire Safety Components and Systems*. Journal of Fire Protection Engineering May 2002. **Vol. 12**: p. 63 - 76.
81. Taylor, K.T., *Office Building Fires... A Case for Automatic Fire Protection*. Fire Journal, Jan/Feb 1990. **Vol. 84**(1): p. 52 - 54.
82. Spearpoint M J, *Fire Protection System Reliability and Effectiveness*. May 2005, Christchurch, New Zealand: University of Canterbury.
83. Koffel, W.E., *Reliability of Automatic Sprinkler Systems*. Sep 2005, Wheaton, IL: Firestop Contractors International Association FCIA.
84. Budnick, E.K., *Automatic sprinkler system reliability*. Fire Protection Engineering. winter 2001: Society of Fire Protection Engineers,.
85. Rohr, K.D. and J.R. Hall, *U.S. experience with sprinklers and other fire extinguishing equipment*. Aug 2005, Quincy, MA: National Fire Protection Association,.
86. Richardson, J.K., *The Reliability of Automatic Sprinkler Systems*. Vol. 238. Jul 1985: Canadian Building Digests.
87. Risk Logic Inc., *Fire Protection Statistics* Jan 2006, Woodcliff Lake, NJ: http://www.risklogic.com/Jan2006.html.
88. Miller, M.J., *Reliability of Fire Protection Systems*. Loss Prevention ACEP Teclznical Manual, 1974. **Vol. 8**: p. 85 - 90.

89. Marryatt, H.W., et al., *Fire: a century of automatic sprinkler protection in Australia and New Zealand 1886-1986*. 1988, North Melbourne, Vic: Australian Fire Protection Association in co-operation with National Fire Protection Association International and National Fire Sprinklers Association Inc. U.S.A. 478.

90. Australian and New Zealand Standard, *AS/NZS 4360:1999 : Risk management* 1999.

91. Allan, D.J., *Fires and Explosions in Substations.* IEEE Xplore, Oct 2002.

92. Ainsorth, S., et al., *Guidance on the prevention and control of fire and explosion at mines used for storage and other purposes.* Health and Safety Executive, 2002.

93. Barry, T.F., *Risk-informed, performance-based industrial fire protection : an alternative to prescriptive codes*. 1st ed. 2002, Knoxville, Tenn.: Tennessee Valley Pub. 1 v. (various pagings).

94. United States Coast Guard, *Risk - Based Decision-Making Guidelines - Event Tree Analysis 3rd Ed.* 2007. **Vol 3 Ch 10**.

95. Haag, D., *Guidelines for quantitive risk assessment - Purple Book.* 1st ed. Committee for the Prevention of Disasters, ed. CPR 18E. 1999.

96. Bennetts, I.D., et al., *Fire Safety In Shopping Centres - Project 6.* Fire Code Reform Research Program, July 1998.

97. Hurley, P., *Private communication*. 2006, ABB New Zealand Ltd.: New Zealand.

98. Aldy, J.E. and W.K. Viscusi, *Adjusting the Value of a Statistical Life for Age and Cohort Effect.* Resources For the Future 2006(RFF DP 06-19).

99. Alberta Fire Commissioner, *Fire deaths in Alberta: 2001-05* Government of Alberta. 2006, Canadian: http://www.municipalaffairs.gov.ab.ca/fco_FireCommStats.htm.

100. Fontana, M., et al., *Final proceedings, SFPE Symposium on Risk, Uncertainty, and Reliability in Fire Protection Engineering and SFPE/Clark University/NSF Workshop on Encouraging the Use of Risk Concepts in Performance-Based Building and Fire Regulation Development - Fire Statistics*. May 1999, [Boston, Mass.]: Society of Fire Protection Engineers. iii, 280.

101. Barker, H.R., *Annual Report 2005.* New Zealand Fire Service Commission, Jun 2005: p. 9.

102. Munor, I., *Private communication*. 2007, Metropolitan Fire Brigade: Victoria, Australia.

103. ABB Power Transmission Pty Ltd., *Resibloc: Epoxy resin transformers.*

104. Karlsson, B. and J.G. Quintiere, *Enclosure fire dynamics*. 2000, Boca Raton, FL: CRC Press. 315.

105. Office of the Deputy Prime Minister, *The Economic Cost of Fire: Estimates for 2004.* UK, Apr 2006.
106. Ashe, W., J. McAneney, and J. Pitman, *The cost of fire in Australia.* Australia, 2006.
107. Krupnick, A., *Mortality Risk valuation for Air Quality Policy*. Resources For the Future, Oct 2006.
108. Slayter, T., *Economics Costs of Natural Disasters in Australia.* Bureau of Transport Economics, Report 103, Commonwealth of Australia, 2001.
109. Danish Emergency Management Agency, *The socio-economic costs of fire in Denmark.* Denmark, Apr 2001.
110. Ministry of Transport, *The social cost of road crashes and injuries*. Jun 2005, New Zealand: Ministry of Transport.
111. AUSTROADS., *Benefit cost analysis manual*. AUSTROADS publication ; no. AP-42/96. 1996, Sydney, N.S.W.: Austroads. iii, 59.
112. Guy, B. and S. Shell, *Design for Deconstruction and Materials Reuse*. 2002: https://www.denix.osd.mil/denix/Public/Library/Sustain/BDC/Documents/design_for_decon.pdf.
113. ABB Power Transmission Pty Ltd., *IEC 61850 - Long term stability*. Dec 2005: http://www.abb.com/cawp/seitp202/c1256a8c00499292c1256d41003853c2.aspx?leftdb=abbzh250&v=553e&e=&.
114. Rawlinsons Media Ltd, *2004 Rawlinsons New Zealand Construction Handbook:*. 19 ed. Rawlinsons Media Ltd. 2004, New Zealand.
115. Buckley, T., *Private communication*. 2006, Ove Arup Pty Ltd.: Victoria, Australia.
116. Puchovsky, M.T., *Automatic Sprinkler System*. Fire Protection Handbook, ed. ed.19. Vol. 2. 2003, Massachusetts, USA: NFPA. p10-185 - p.10-211.
117. Australian Standard, *AS 1851: 2005 - Maintenance of fire protection systems and equipment.* 2005.
118. Sydenham, C., *Private communication*. 2006, Integrity Fire Protection P/L: Victoria, Australia.
119. Hydroelectric Research and Technical Services Group, *FIST 3-32: Transformer Fire Protection*. Vol. 3-32. 2005, Denver, CO: U.S. Department of Interior, Bureau of Reclamation.

APPENDIX A: Transformer and Associated Equipment

Appendix A1 - Site Visit (1): Christchurch city centre

Figure A1.1: 750kVA mineral oil fluid transformer

Figure A1.2: Circuit board

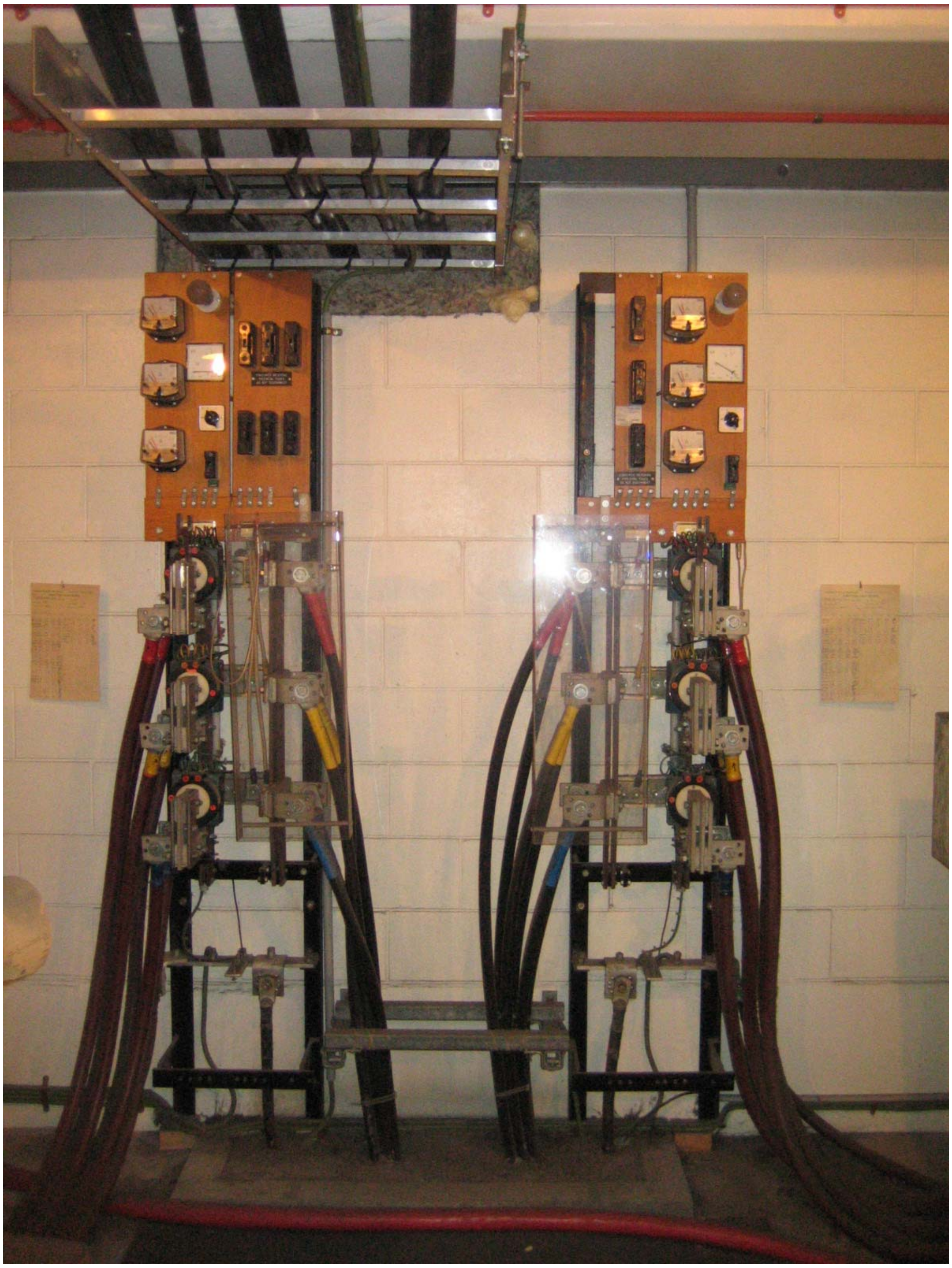


Figure A1.3: Cables terminal

Figure A1.4: High voltage switchgear

Figure A1.5: Low voltage switchgear

Figure A1.6: Cable tray

Appendix A2 - Site visit (2): University of Canterbury

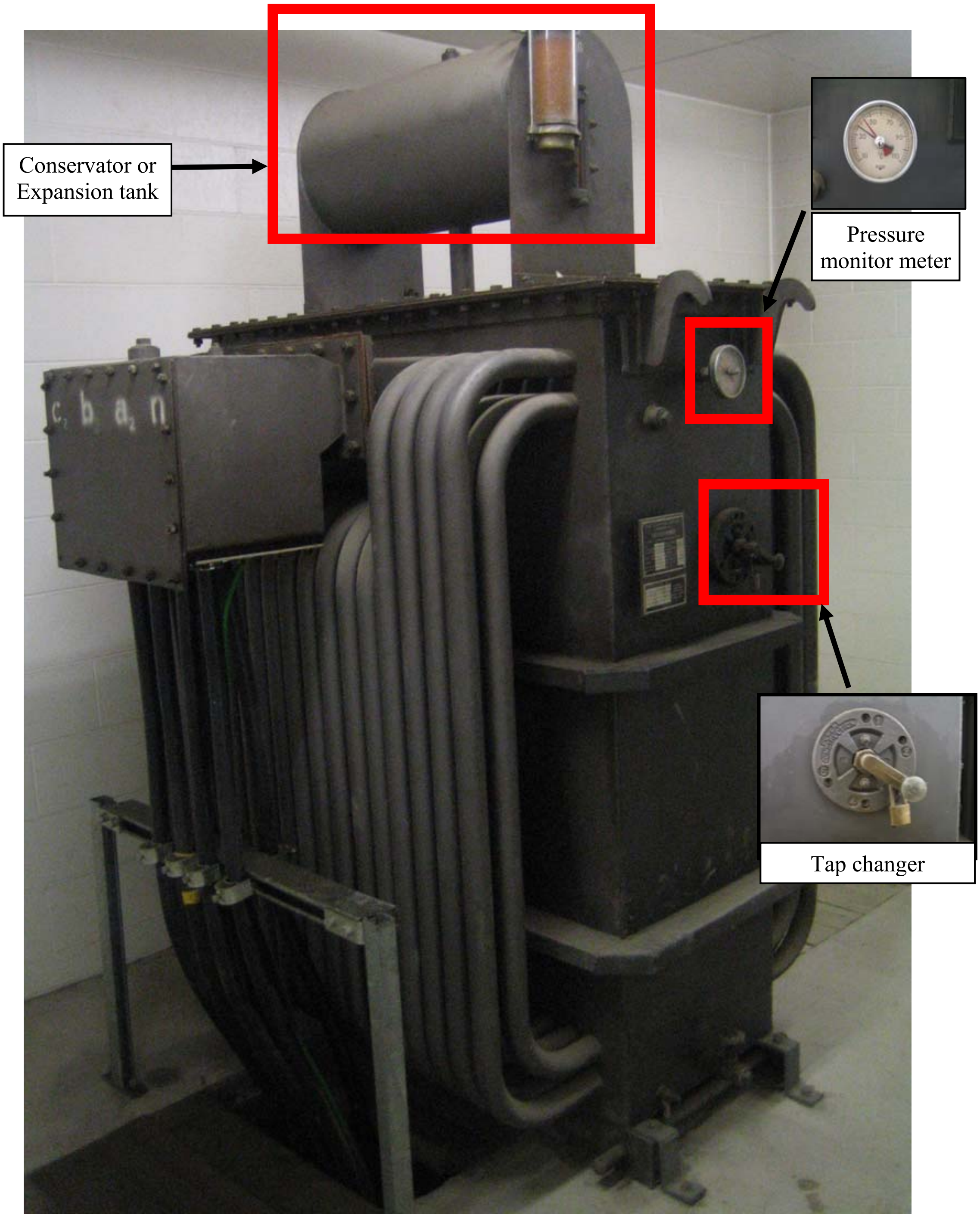


Figure A2.1: 750kVA mineral oil fluid transformer on an oil containment

Figure A2.2: Oil insulated high voltage switchgear

Figure A2.3: Low voltage switchgear

Figure A2.4: Wall opening in a distribution station

Figure A2.5: Combustible material (wooden board) in a distribution substation

APPENDIX B: Distribution Substation Fire Safety Protection Required by the NZFS

1) *Place transformers and switchgear in separate rooms within vaults* (distribution substation). *A fire resistance rating of not less than F60 (1 hour rating) should apply to these partitions and all openings and penetrations in them.*

2) *Separate vaults* (distribution substation) *from the interior spaces of buildings by walls and floor/ceiling assemblies having fire resistance ratings not less than F240 (4-hour rating) with suitable fire resistance rated protection of all openings and penetrations.*

3) *Provide direct exterior access to transformer vaults* (distribution substation) *by means of a full-sized door (minimum clear opening area of 800 x 2100mm) wherever possible.*

4) *Cable penetrations in fire resistance rated walls separating other interior spaces of the building from the vaults* (distribution substation) *should occur within 1.0m of the floor to avoid placing openings near ceilings where smoke, flames and heated gases may accumulate and spread in a fire situation.*

5) *No penetrations should be permitted in the floor/ceiling assemblies separating a vault* (distribution substation) *from upper floors, and if at all possible installations in basements should be avoided altogether.*

6) *Cable feeds into equipment should be from the top rather than the bottom to avoid placing cables in an area where burning transformer oil or fire suppression water may pool.*

7) *Transformers and switchgear should be installed on plinths or platforms above the floor level to prevent connections inside equipment cabinets from coming into contact with burning transformer oil or fire suppression water.*

8) *Bunding of sufficient capacity to contain the contents of the largest transformer and a quantity of fire suppression water equal to that expected for 20 minutes flow from manual or automatic appliances should be provided.*

9) *Install a sump pit and suction connection to provide for the removal of oil and water from the room without the need for entry.*

10) *In building protected by automatic sprinkler systems, provide automatic sprinkler protection for transformer rooms within vaults* (distribution substation). *Provide gas flood or water mist systems in switchgear room.*

11) *Provide deflagration venting direct to the building exterior from transformer rooms within vaults* (distribution substation) *or design the room to withstand and contain the pressure developed from a transformer explosion within the space.*

12) *In buildings without automatic fire sprinkler systems, no additional fire protection need be installed beyond that required by the New Zealand Building Code. Nevertheless, we strongly encourage "the company" to install automatic heat detection in these and subscribe to appropriate monitoring and notification services to obtain early warning of a fire that may affect the reliability of the distribution grid.*

New Zealand fire Service - Whakaratonga Iwi
Christchurch,
New Zealand

APPENDIX C: Statistical data of Transformer Fires in Distribution Substations

The table below shows the statistical data for the number of distribution substations in New Zealand between 1946 and 1995 and the estimated number of distribution substations between 1996 and 2006. Refer to the New Zealand Energy and Resources Division and Market Information and Analysis Group [70], the New Zealand Energy Modelling and Statistics Unit [71] and [72], and the New Zealand Ministry of Energy [73]

Year ending 31st March	Number of substations	Year ending 31st March	Number of substations
1946	23559	1977	97961
1947	24361	1978	101010
1948	25271	1979	103586
1949	26395	1980	106056
1950	27795	1981	108581
1951	28880	1982	111135
1952	30350	1983	113548
1953	31931	1984	116212
1954	33787	1985	119159
1955	36112	1986	121954
1956	38277	1987	124864
1957	40415	1988	119008
1958	42643	1989	127262
1959	44702	1990	128918
1960	46911	1991	130948
1961	49312	1992	134205
1962	51838	1993	133692
1963	54377	1994	135656
1964	56645	1995	138695
1965	58200	1996	141330
1966	62318	1997	144015
1967	65624	1998	146752
1968	68687	1999	149540
1969	71300	2000	152381
1970	74847	2001	155277
1971	78143	2002	158227
1972	81677	2003	161233
1973	84647	2004	164297
1974	87839	2005	167418
1975	90925	2006	170599
1976	94671		

The following tables show the data on distribution substation fire incidents recorded by the NZFS FIRS between 2000 and 2006 [65].

Number of fires

Year	Number of fires
January 2000 - January 2001	4
January 2001 - January 2002	0
January 2002 - January 2003	5
January 2003 - January 2004	4
January 2004 - January 2005	3
January 2005 - January 2006	4

Monthly trends

Month	Number of fires
January	3
February	1
March	1
April	0
May	1
June	4
July	3
August	2
September	1
October	1
November	1
December	2

Time of day

Time period of day	Number of fires
23:00 ~ 03:00	3
03:00 ~ 07:00	3
07:00 ~ 11:00	5
11:00 ~ 15:00	4
15:00 ~ 19:00	2
19:00 ~ 23:00	3

Supposed Causes

Supposed causes	Number of fires	
Electrical failure	12	60.0%
Lack of maintenance	1	5.0%
Equipment overloaded (includes electric cords serving too many appliances)	4	20.0%
Mechanical failure or malfunction	2	10.0%
Unknown	1	5.0%

Primary ignition object

Item First Ignited	Number of fires	
Electrical wire, Wiring insulation	13	65.0%
Transformer, Transformer fluids	4	20.0%
Other known item first ignited	3	15.0%

Equipment involved

[1] Equipment involved	Number of fires	
Transformer & associated equipment - Circuit breakers associated with transformers	4	20.0%
Transformer & associated equipment - Distribution type	7	35.0%
Transformers & associated equipment - not classified above	1	5.0%
Information not recorded	6	30.0%
Other known equipment: Power cable, controlling switch	2	10.0%

[1] This provides a classification for the equipment that provided the heat that started the fire, or was involved in the release of hazardous substances; the equipment involved in the incident is to be listed when it is identified as providing the heat that started fire or was the cause of the incident;

Source of ignition (Heating source)

[1] Heat source	Number of fires	
Short circuit arc	12	60.0%
Arc from fault, loose or broken conductor	2	10.0%
Heat from overloaded equipment	2	10.0%
Other known heat source	4	20.0%

[1] This provides a classification for the form of heat energy igniting the fire e.g. flame, spark or hot surface

Extent flame damage

Extent of flame damage	Number of fires
No damage of this type	0
Confined to object of origin	5
Confined to room of origin	1
Confined to structure of origin	6
Unknown	8

Extent smoke damage

Extent of smoke damage	Number of fires
No damage of this type	3
Confined to object of origin	1
Confined to part of room or area of origin	1
Confined to room of origin	2
Confined to structure of origin	5
Unknown	8

The table below shows the statistical data on the consequence of transformer fire incidents recorded in the NFIRS between 1980 and 2002 [66].

Year	Number of transformer fires	Number of Deaths	Number of injuries	Direct Property Damage (Million)	
				(million NZ$)	(x1000 NZD$/ fire)
1980	1890	15	48	52.0	27.5
1981	1730	5	91	52.3	30.2
1982	1770	0	50	54.2	30.6
1983	1580	0	95	45.1	28.6
1984	1650	0	174	49.3	29.9
1985	1650	2	84	37.3	22.6
1986	1520	8	94	46.5	30.6
1987	1480	2	91	59.8	40.4
1988	1280	4	69	67.5	52.7
1989	1310	2	77	49.7	38.0
1990	1240	5	72	45.9	37.0
1991	1100	0	57	53.6	48.7
1992	1260	0	121	55.5	44.1
1993	1090	0	103	76.2	69.9
1994	1180	1	85	31.5	26.7
1995	1000	0	93	55.5	55.5
1996	1000	0	35	42.5	42.5
1997	990	6	26	45.3	45.7
1998	1030	3	28	67.2	65.2
1999	880	6	41	20.0	22.8
2000	730	0	55	27.7	37.9
2001	730	2	31	69.8	95.6
2002	680	0	18	56.0	82.4
Average	1250.9	2.7	71.2	50.5	40.3

APPENDIX D: Calculation of the Probability of Manual Fire Fighting Performance

The probability that the Fire Service can control fires is found in Fontana et al. [100]. As stated, the probability that fire spread is stopped by fire firefighters for general buildings is in the range of 0.8 to 0.95. Since the research only provides details on the P_{MFF} for commercial buildings, the ratio between the P_{MFF} in different situation for commercial buildings is used to determine the P_{MFF} for general buildings. The calculations are shown in Table D-1.

[1] Commercial building					
Firefighters' ability	Early warning alarm	P_{MFF_S} (t_{a_a} < 10 minutes)	Ratio	P_{MFF_S} (t_{a_a} > 10 minutes)	Ratio
Professional	Not provided	0.95	0.95/0.95 = **100%**	0.85	0.85/0.95 = **89.5%**
Professional	Provided	0.988	0.988/0.95 = **104%**	0.963	0.963/0.95 = **101.4%**

[1] The performance of P_{MFF} is given for commercial building. Use it as a base and determined the ratio.

General building **Upper bound** (P_{MFF} = 0.95 where professional firefighter and no early warning alarm provided)			
Firefighters' ability	Early warning alarm	P_{MFF_S} (t_{a_a} < 10 minutes)	P_{MFF_S} (t_{a_a} > 10 minutes)
Professional	Not provided	0.95 * 100% = **0.95**	0.95 * 89.5% = **0.85**
Professional	Provided	0.95 * 104% = **0.988**	0.95 * 101.4% = **0.963**
General building **Lower bound** (P_{MFF} = 0.80 where professional firefighter and no early warning alarm provided)			
Firefighters' ability	Early warning alarm	P_{MFF_S} (t_{a_a} < 10 minutes)	P_{MFF_S} (t_{a_a} > 10 minutes)
Professional	Not provided	0.80 * 100% = **0.80**	0.80 * 89.5% = **0.761**
Professional	Provided	0.80 * 104% = **0.832**	0.80 * 101.4% = **0.811**

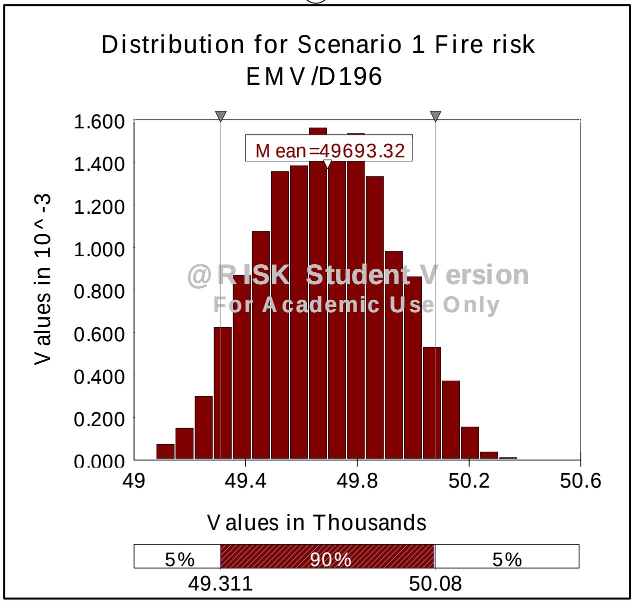
Same approach is used to determine the probability of the non-professional firefighter controlling the fire. The overall results are shown in Table D-2 as follow:

General building			
Firefighters' ability	Early warning alarm	P_{MFF_S} (t_{a_a} <10 min)	P_{MFF_S} (t_{a_a} >10 minutes)
Professional firefighters	Not provided	80.0% - 95.0%	71.6% - 85.0%
Non-professional firefighters	Not provided	75.8% - 90.0%	67.4% - 80.0%
Professional firefighters	Provide	83.2% - 98.8%	81.1% - 96.3%
Non-professional firefighters	Provide	82.1% - 97.5%	71.6% - 85.0%

APPENDIX E: Probability Distribution of the Total Risk for each scenario

Scenario 1: No sprinkler system, 30 minute FRR, Mineral oil insulated transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ transformer fire incident**
1	0.855	0.000	-----------	-----------	1.000	0.00000	31000	0
2	0.855	1.000	0.403	0.800	1.000	0.27602	47750	13180
3	0.855	1.000	0.403	0.200	0.000	0.00000	47750	0
4	0.855	1.000	0.403	0.200	1.000	0.06900	55300	3816
5	0.855	1.000	0.597	0.777	1.000	0.39659	47750	18937
6	0.855	1.000	0.597	0.223	0.000	0.00000	47750	0
7	0.855	1.000	0.597	0.223	1.000	0.11382	55300	6294
8	0.145	0.000	-----------	-----------	1.000	0.00000	30300	0
9	0.145	1.000	0.403	0.765	1.000	0.04461	48775	2176
10	0.145	1.000	0.403	0.235	0.000	0.00000	48775	0
11	0.145	1.000	0.403	0.235	1.000	0.01370	58650	804
12	0.145	1.000	0.597	0.673	1.000	0.05805	48775	2831
13	0.145	1.000	0.597	0.327	0.000	0.00000	48775	0
14	0.145	1.000	0.597	0.327	1.000	0.02821	58650	1654
					Total:	***1.00000***	***Total:***	***49692***
Note that the values above only show the mean values of the distributions.								

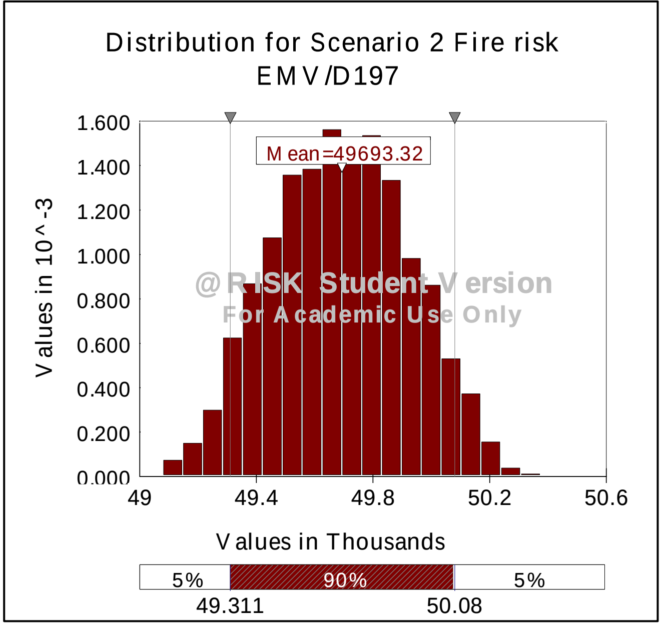
Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 49,013	5%	$ 49,311
Maximum	$ 50,446	50%	$ 49,376
Mean	$ 49,693	95%	$ 49,436
Std Dev	$ 235		

Scenario 2: No sprinkler system, 1 hour FRR, Mineral oil insulated transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ transformer fire incident**
1	0.855	0.000	-----------	-----------	1.000	0.00000	31000	0
2	0.855	1.000	0.403	0.800	1.000	0.27602	47750	13180
3	0.855	1.000	0.403	0.200	0.000	0.00000	47750	0
4	0.855	1.000	0.403	0.200	1.000	0.06900	55300	3816
5	0.855	1.000	0.597	0.777	1.000	0.39659	47750	18937
6	0.855	1.000	0.597	0.223	0.000	0.00000	47750	0
7	0.855	1.000	0.597	0.223	1.000	0.11382	55300	6294
8	0.145	0.000	-----------	-----------	1.000	0.00000	30300	0
9	0.145	1.000	0.403	0.765	1.000	0.04461	48775	2176
10	0.145	1.000	0.403	0.235	0.000	0.00000	48775	0
11	0.145	1.000	0.403	0.235	1.000	0.01370	58650	804
12	0.145	1.000	0.597	0.673	1.000	0.05805	48775	2831
13	0.145	1.000	0.597	0.327	0.000	0.00000	48775	0
14	0.145	1.000	0.597	0.327	1.000	0.02821	58650	1654
					Total:	***1.00000***	***Total:***	***49692***
Note that the values above only show the mean values of the distributions.								

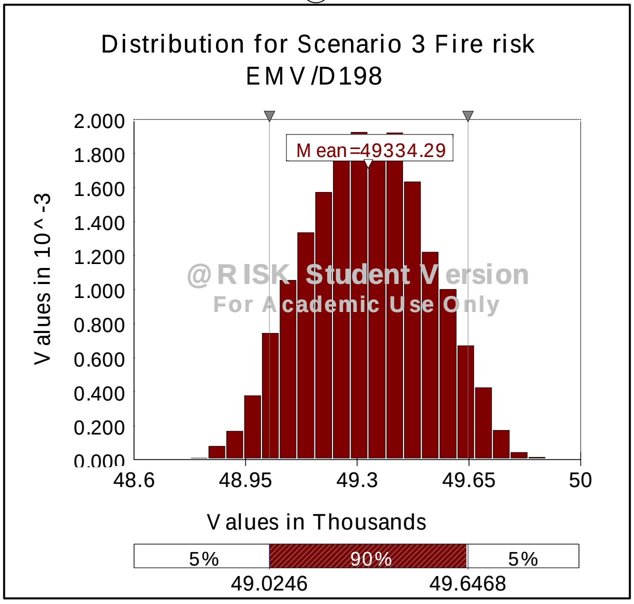
Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 49,013	5%	$ 49,311
Maximum	$ 50,446	50%	$ 49,376
Mean	$ 49,693	95%	$ 49,436
Std Dev	$ 235		

Scenario 3: No sprinkler system, 2 hour FRR, Mineral oil insulated transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ transformer fire incident**
1	0.855	0.000	-----------	-----------	1.000	0.00000	31000	0
2	0.855	1.000	0.403	0.800	1.000	0.27602	47750	13180
3	0.855	1.000	0.403	0.200	0.200	0.01380	47750	659
4	0.855	1.000	0.403	0.200	0.800	0.05520	55300	3053
5	0.855	1.000	0.597	0.777	1.000	0.39659	47750	18937
6	0.855	1.000	0.597	0.223	0.200	0.02276	47750	1087
7	0.855	1.000	0.597	0.223	0.800	0.09106	55300	5035
8	0.145	0.000	-----------	-----------	1.000	0.00000	30300	0
9	0.145	1.000	0.403	0.765	1.000	0.04461	48775	2176
10	0.145	1.000	0.403	0.235	0.200	0.00274	48775	134
11	0.145	1.000	0.403	0.235	0.800	0.01096	58650	643
12	0.145	1.000	0.597	0.673	1.000	0.05805	48775	2831
13	0.145	1.000	0.597	0.327	0.200	0.00564	48775	275
14	0.145	1.000	0.597	0.327	0.800	0.02257	58650	1323
					Total:	***1.00000***	***Total:***	***49334***
Note that the values above only show the mean values of the distributions.								

Simulation result from @Risk4.5



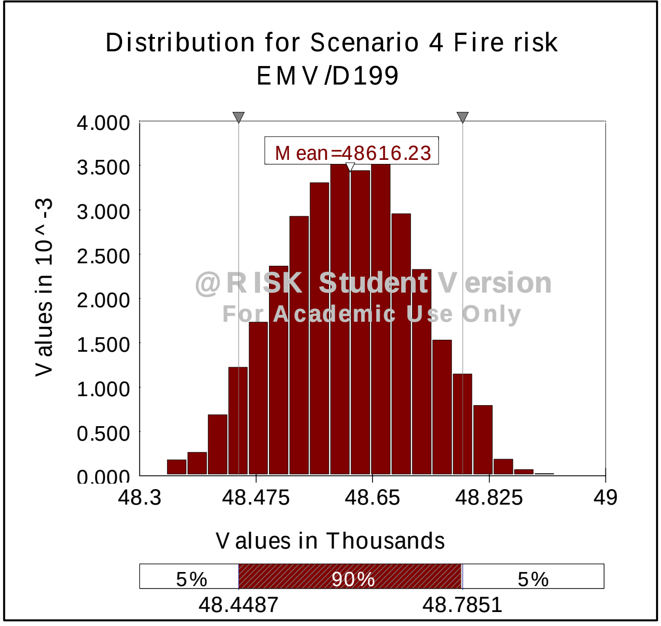
Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 48,779	5%	$ 49,025
Maximum	$ 49,949	50%	$ 49,079
Mean	$ 49,334	95%	$ 49,126
Std Dev	$ 190		

Scenario 4: No sprinkler system, 3 hour FRR, Mineral oil insulated transformer

Outcome event No.	SDS	SS	FAT	MFF	WBI	Probability of each outcome	Consequence EMV (NZD$)	Risk NZD$/ transformer fire incident
1	0.855	0.000	-----------	-----------	1.000	0.00000	31000	0
2	0.855	1.000	0.403	0.800	1.000	0.27602	47750	13180
3	0.855	1.000	0.403	0.200	0.600	0.04140	47750	1977
4	0.855	1.000	0.403	0.200	0.400	0.02760	55300	1526
5	0.855	1.000	0.597	0.777	1.000	0.39659	47750	18937
6	0.855	1.000	0.597	0.223	0.600	0.06829	47750	3261
7	0.855	1.000	0.597	0.223	0.400	0.04553	55300	2518
8	0.145	0.000	-----------	-----------	1.000	0.00000	30300	0
9	0.145	1.000	0.403	0.765	1.000	0.04461	48775	2176
10	0.145	1.000	0.403	0.235	0.600	0.00822	48775	401
11	0.145	1.000	0.403	0.235	0.400	0.00548	58650	321
12	0.145	1.000	0.597	0.673	1.000	0.05805	48775	2831
13	0.145	1.000	0.597	0.327	0.600	0.01692	48775	825
14	0.145	1.000	0.597	0.327	0.400	0.01128	58650	662
					Total:	***1.00000***	***Total:***	***48616***

Note that the values above only show the mean values of the distributions.

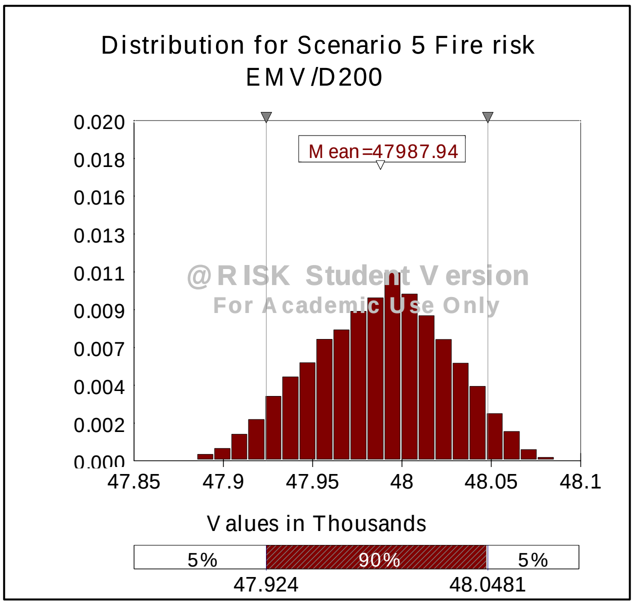
Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 48,311	5%	$ 48,449
Maximum	$ 48,955	50%	$ 48,482
Mean	$ 48,616	95%	$ 48,506
Std Dev	$ 102		

Scenario 5: No sprinkler system, 4 hour FRR, Mineral oil insulated transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ transformer fire incident**
1	0.855	0.000	-----------	-----------	1.000	0.00000	31000	0
2	0.855	1.000	0.403	0.800	1.000	0.27602	47750	13180
3	0.855	1.000	0.403	0.200	0.950	0.06555	47750	3130
4	0.855	1.000	0.403	0.200	0.050	0.00345	55300	191
5	0.855	1.000	0.597	0.777	1.000	0.39659	47750	18937
6	0.855	1.000	0.597	0.223	0.950	0.10813	47750	5163
7	0.855	1.000	0.597	0.223	0.050	0.00569	55300	315
8	0.145	0.000	-----------	-----------	1.000	0.00000	30300	0
9	0.145	1.000	0.403	0.765	1.000	0.04461	48775	2176
10	0.145	1.000	0.403	0.235	0.950	0.01302	48775	635
11	0.145	1.000	0.403	0.235	0.050	0.00069	58650	40
12	0.145	1.000	0.597	0.673	1.000	0.05805	48775	2831
13	0.145	1.000	0.597	0.327	0.950	0.02680	48775	1307
14	0.145	1.000	0.597	0.327	0.050	0.00141	58650	83
					Total:	***1.00000***	***Total:***	***47988***
Note that the values above only show the mean values of the distributions.								

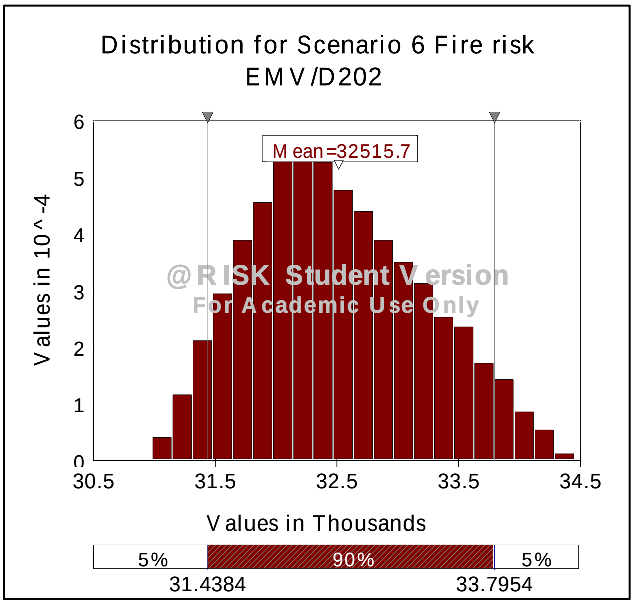
Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 47,886	5%	$ 47,924
Maximum	$ 48,086	50%	$ 47,937
Mean	$ 47,988	95%	$ 47,946
Std Dev	$ 37		

Scenario 6: Sprinkler system, 30 minute FRR, Mineral oil insulated transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ transformer fire incident**
1	0.855	0.914	-----------	-----------	1.000	0.78184	31000	24237
2	0.855	0.086	0.403	0.800	1.000	0.02375	47750	1134
3	0.855	0.086	0.403	0.200	0.000	0.00000	47750	0
4	0.855	0.086	0.403	0.200	1.000	0.00594	55300	328
5	0.855	0.086	0.597	0.777	1.000	0.03412	47750	1629
6	0.855	0.086	0.597	0.223	0.000	0.00000	47750	0
7	0.855	0.086	0.597	0.223	1.000	0.00979	55300	542
8	0.145	0.914	-----------	-----------	1.000	0.13213	30300	4004
9	0.145	0.086	0.403	0.765	1.000	0.00384	48775	187
10	0.145	0.086	0.403	0.235	0.000	0.00000	48775	0
11	0.145	0.086	0.403	0.235	1.000	0.00118	58650	69
12	0.145	0.086	0.597	0.673	1.000	0.00499	48775	244
13	0.145	0.086	0.597	0.327	0.000	0.00000	48775	0
14	0.145	0.086	0.597	0.327	1.000	0.00243	58650	142
					Total:	***1.00000***	***Total:***	***32516***
Note that the values above only show the mean values of the distributions.								

Simulation result from @Risk4.5



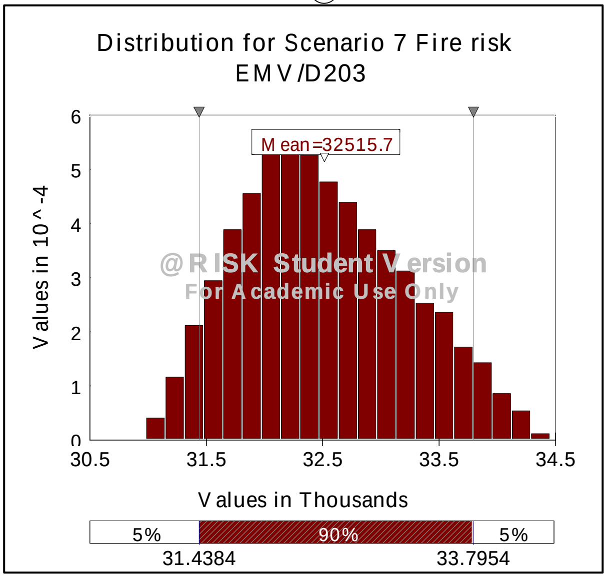
Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 30,988	5%	$ 31,438
Maximum	$ 34,459	50%	$ 31,621
Mean	$ 32,516	95%	$ 31,759
Std Dev	$ 711		

Scenario 7: Sprinkler system, 1 hour FRR, Mineral oil insulated transformer

Outcome event No.	SDS	SS	FAT	MFF	WBI	Probability of each outcome	Consequence EMV (NZD$)	Risk NZD$/ transformer fire incident
1	0.855	0.914	-----------	-----------	1.000	0.78184	31000	24237
2	0.855	0.086	0.403	0.800	1.000	0.02375	47750	1134
3	0.855	0.086	0.403	0.200	0.000	0.00000	47750	0
4	0.855	0.086	0.403	0.200	1.000	0.00594	55300	328
5	0.855	0.086	0.597	0.777	1.000	0.03412	47750	1629
6	0.855	0.086	0.597	0.223	0.000	0.00000	47750	0
7	0.855	0.086	0.597	0.223	1.000	0.00979	55300	542
8	0.145	0.914	-----------	-----------	1.000	0.13213	30300	4004
9	0.145	0.086	0.403	0.765	1.000	0.00384	48775	187
10	0.145	0.086	0.403	0.235	0.000	0.00000	48775	0
11	0.145	0.086	0.403	0.235	1.000	0.00118	58650	69
12	0.145	0.086	0.597	0.673	1.000	0.00499	48775	244
13	0.145	0.086	0.597	0.327	0.000	0.00000	48775	0
14	0.145	0.086	0.597	0.327	1.000	0.00243	58650	142
					Total:	***1.00000***	***Total:***	***32516***

Note that the values above only show the mean values of the distributions.

Simulation result from @Risk4.5



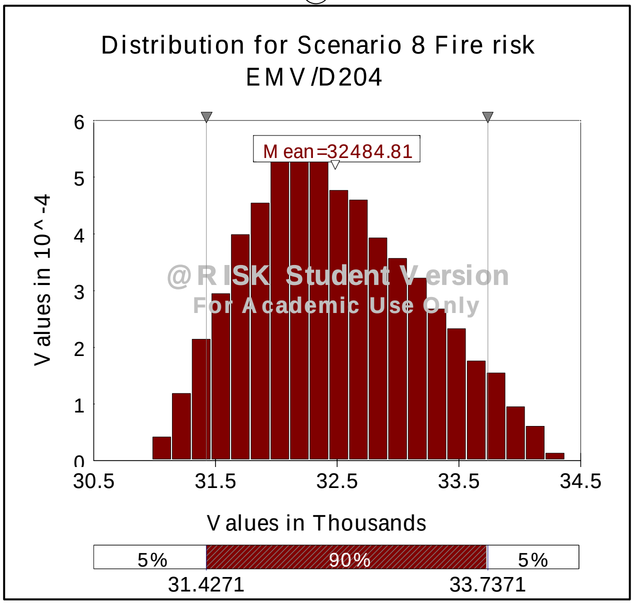
Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 30,988	5%	$ 31,438
Maximum	$ 34,459	50%	$ 31,621
Mean	$ 32,516	95%	$ 31,759
Std Dev	$ 711		

Scenario 8: Sprinkler system, 2 hour FRR, Mineral oil insulated transformer

Outcome event No.	SDS	SS	FAT	MFF	WBI	Probability of each outcome	Consequence EMV (NZD$)	Risk NZD$/ transformer fire incident
1	0.855	0.914	-----------	-----------	1.000	0.78184	31000	24237
2	0.855	0.086	0.403	0.800	1.000	0.02375	47750	1134
3	0.855	0.086	0.403	0.200	0.200	0.00119	47750	57
4	0.855	0.086	0.403	0.200	0.800	0.00475	55300	263
5	0.855	0.086	0.597	0.777	1.000	0.03412	47750	1629
6	0.855	0.086	0.597	0.223	0.200	0.00196	47750	94
7	0.855	0.086	0.597	0.223	0.800	0.00783	55300	433
8	0.145	0.914	-----------	-----------	1.000	0.13213	30300	4004
9	0.145	0.086	0.403	0.765	1.000	0.00384	48775	187
10	0.145	0.086	0.403	0.235	0.200	0.00024	48775	11
11	0.145	0.086	0.403	0.235	0.800	0.00094	58650	55
12	0.145	0.086	0.597	0.673	1.000	0.00499	48775	244
13	0.145	0.086	0.597	0.327	0.200	0.00049	48775	24
14	0.145	0.086	0.597	0.327	0.800	0.00194	58650	114
					Total:	***1.00000***	***Total:***	***32485***

Note that the values above only show the mean values of the distributions.

Simulation result from @Risk4.5



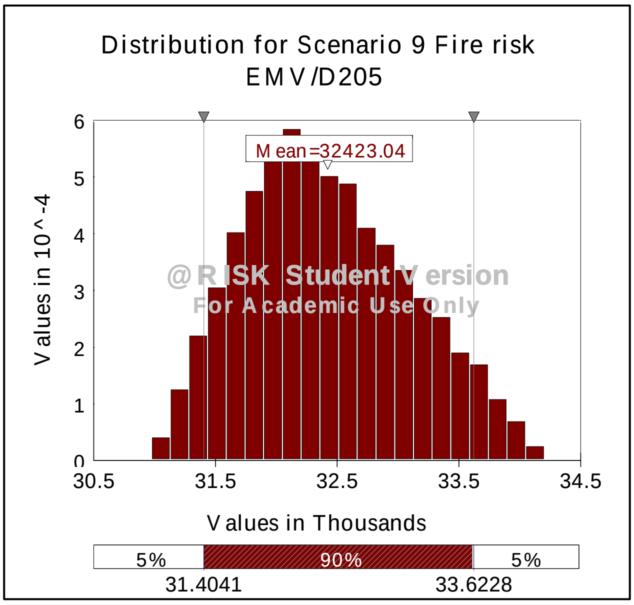
Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 30,986	5%	$ 31,427
Maximum	$ 34,376	50%	$ 31,607
Mean	$ 32,485	95%	$ 31,743
Std Dev	$ 698		

Scenario 9: Sprinkler system, 3 hour FRR, Mineral oil insulated transformer

Outcome event No.	SDS	SS	FAT	MFF	WBI	Probability of each outcome	Consequence EMV (NZD$)	Risk NZD$/ transformer fire incident
1	0.855	0.914	-----------	-----------	1.000	0.78184	31000	24237
2	0.855	0.086	0.403	0.800	1.000	0.02375	47750	1134
3	0.855	0.086	0.403	0.200	0.600	0.00356	47750	170
4	0.855	0.086	0.403	0.200	0.400	0.00237	55300	131
5	0.855	0.086	0.597	0.777	1.000	0.03412	47750	1629
6	0.855	0.086	0.597	0.223	0.600	0.00588	47750	281
7	0.855	0.086	0.597	0.223	0.400	0.00392	55300	217
8	0.145	0.914	-----------	-----------	1.000	0.13213	30300	4004
9	0.145	0.086	0.403	0.765	1.000	0.00384	48775	187
10	0.145	0.086	0.403	0.235	0.600	0.00071	48775	34
11	0.145	0.086	0.403	0.235	0.400	0.00047	58650	28
12	0.145	0.086	0.597	0.673	1.000	0.00499	48775	244
13	0.145	0.086	0.597	0.327	0.600	0.00146	48775	71
14	0.145	0.086	0.597	0.327	0.400	0.00097	58650	57
					Total:	***1.00000***	***Total:***	***32423***

Note that the values above only show the mean values of the distributions.

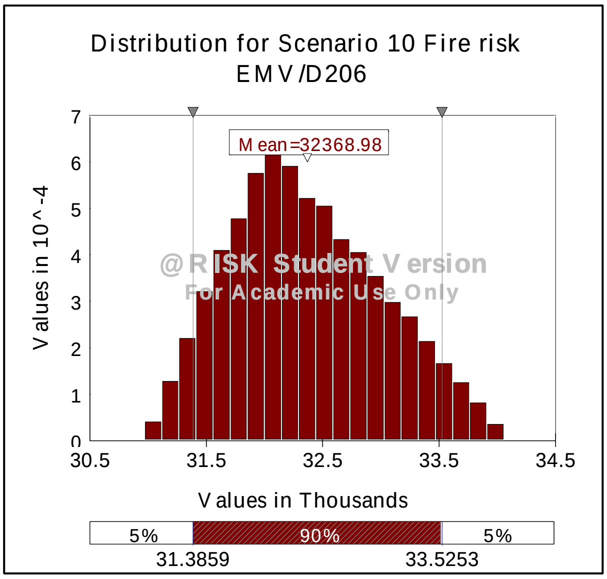
Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 30,981	5%	$ 31,404
Maximum	$ 34,209	50%	$ 31,580
Mean	$ 32,423	95%	$ 31,712
Std Dev	$ 671		

Scenario 10: Sprinkler system, 4 hour FRR, Mineral oil insulated transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ transformer fire incident**
1	0.855	0.914	-----------	-----------	1.000	0.78184	31000	24237
2	0.855	0.086	0.403	0.800	1.000	0.02375	47750	1134
3	0.855	0.086	0.403	0.200	0.950	0.00564	47750	269
4	0.855	0.086	0.403	0.200	0.050	0.00030	55300	16
5	0.855	0.086	0.597	0.777	1.000	0.03412	47750	1629
6	0.855	0.086	0.597	0.223	0.950	0.00930	47750	444
7	0.855	0.086	0.597	0.223	0.050	0.00049	55300	27
8	0.145	0.914	-----------	-----------	1.000	0.13213	30300	4004
9	0.145	0.086	0.403	0.765	1.000	0.00384	48775	187
10	0.145	0.086	0.403	0.235	0.950	0.00112	48775	55
11	0.145	0.086	0.403	0.235	0.050	0.00006	58650	3
12	0.145	0.086	0.597	0.673	1.000	0.00499	48775	244
13	0.145	0.086	0.597	0.327	0.950	0.00231	48775	112
14	0.145	0.086	0.597	0.327	0.050	0.00012	58650	7
					Total:	***1.00000***	***Total:***	***32369***
Note that the values above only show the mean values of the distributions.								

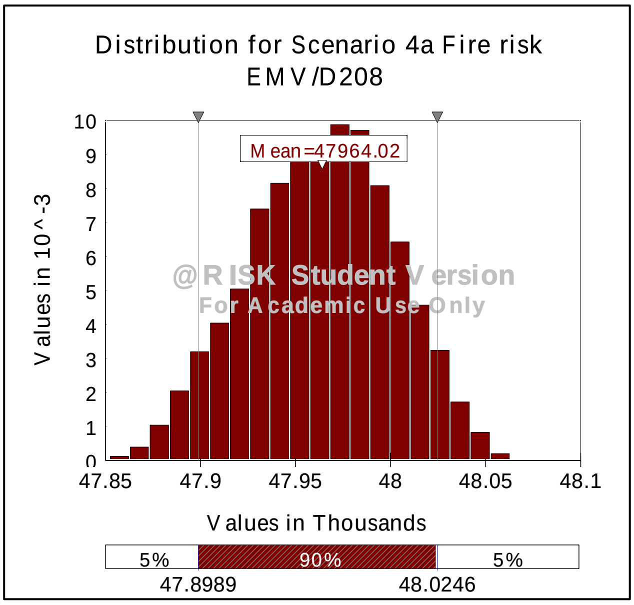
Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 30,977	5%	$ 31,386
Maximum	$ 34,063	50%	$ 31,554
Mean	$ 32,369	95%	$ 31,682
Std Dev	$ 647		

Scenario 4a: No sprinkler system, 3 hour FRR, Silicone oil insulated transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ transformer fire incident**
1	0.855	0.000	-----------	-----------	1.000	0.00000	31000	0
2	0.855	1.000	0.403	0.865	1.000	0.29845	47750	14251
3	0.855	1.000	0.403	0.135	0.949	0.04418	47750	2110
4	0.855	1.000	0.403	0.135	0.051	0.00239	55300	132
5	0.855	1.000	0.597	0.842	1.000	0.42976	47750	20521
6	0.855	1.000	0.597	0.158	0.949	0.07650	47750	3653
7	0.855	1.000	0.597	0.158	0.051	0.00415	55300	229
8	0.145	0.000	-----------	-----------	1.000	0.00000	30300	0
9	0.145	1.000	0.403	0.830	1.000	0.04840	48775	2361
10	0.145	1.000	0.403	0.170	0.949	0.00940	48775	459
11	0.145	1.000	0.403	0.170	0.051	0.00051	58650	30
12	0.145	1.000	0.597	0.738	1.000	0.06366	48775	3105
13	0.145	1.000	0.597	0.262	0.949	0.02144	48775	1046
14	0.145	1.000	0.597	0.262	0.051	0.00116	58650	68
					Total:	***1.00000***	***Total:***	***47964***
Note that the values above only show the mean values of the distributions.								

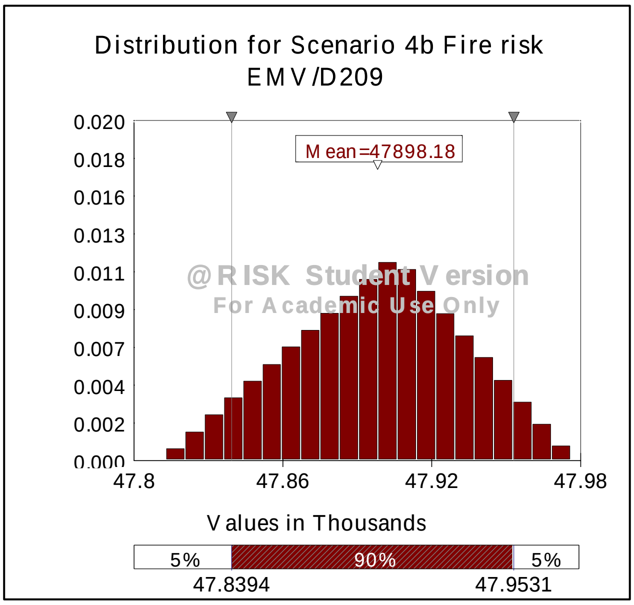
Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 47,852	5%	$ 47,899
Maximum	$ 48,074	50%	$ 47,913
Mean	$ 47,964	95%	$ 47,923
Std Dev	$ 38		

Scenario 4b: No sprinkler system, 3 hour FRR, Dry type transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ transformer fire incident**
1	0.855	0.000	-----------	-----------	1.000	0.00000	31000	0
2	0.855	1.000	0.403	0.910	1.000	0.31397	47750	14992
3	0.855	1.000	0.403	0.090	1.000	0.03105	47750	1483
4	0.855	1.000	0.403	0.090	0.000	0.00000	55300	0
5	0.855	1.000	0.597	0.887	1.000	0.45273	47750	21618
6	0.855	1.000	0.597	0.113	1.000	0.05768	47750	2754
7	0.855	1.000	0.597	0.113	0.000	0.00000	55300	0
8	0.145	0.000	-----------	-----------	1.000	0.00000	30300	0
9	0.145	1.000	0.403	0.875	1.000	0.05102	48775	2488
10	0.145	1.000	0.403	0.125	1.000	0.00729	48775	355
11	0.145	1.000	0.403	0.125	0.000	0.00000	58650	0
12	0.145	1.000	0.597	0.783	1.000	0.06754	48775	3294
13	0.145	1.000	0.597	0.217	1.000	0.01872	48775	913
14	0.145	1.000	0.597	0.217	0.000	0.00000	58650	0
					Total:	***1.00000***	***Total:***	***47898***
Note that the values above only show the mean values of the distributions.								

Simulation result from @Risk4.5



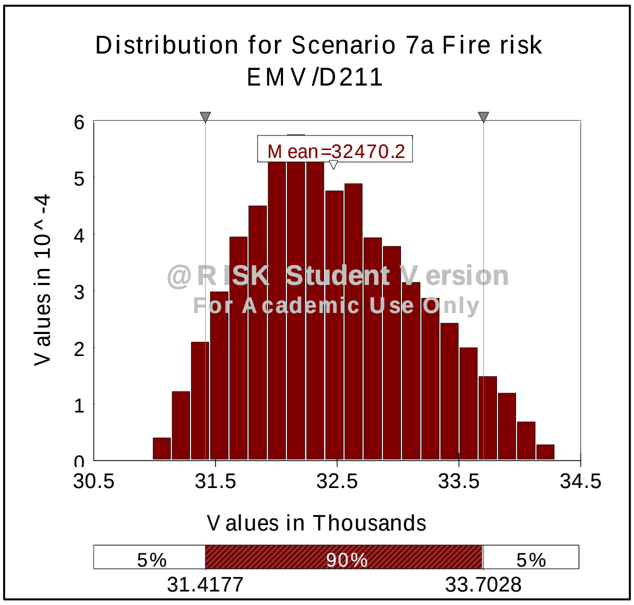
Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 47,813	5%	$ 47,839
Maximum	$ 47,976	50%	$ 47,851
Mean	$ 47,898	95%	$ 47,860
Std Dev	$ 34		

Scenario 7a: Sprinkler system, 1 hour FRR, Silicone oil insulated transformer

Outcome event No.	SDS	SS	FAT	MFF	WBI	Probability of each outcome	Consequence EMV (NZD$)	Risk NZD$/ transformer fire incident
1	0.855	0.914	-----------	-----------	1.000	0.78184	31000	24237
2	0.855	0.086	0.403	0.865	1.000	0.02568	47750	1226
3	0.855	0.086	0.403	0.135	0.010	0.00004	47750	2
4	0.855	0.086	0.403	0.135	0.990	0.00397	55300	219
5	0.855	0.086	0.597	0.842	1.000	0.03697	47750	1766
6	0.855	0.086	0.597	0.158	0.010	0.00007	47750	3
7	0.855	0.086	0.597	0.158	0.990	0.00687	55300	380
8	0.145	0.914	-----------	-----------	1.000	0.13213	30300	4004
9	0.145	0.086	0.403	0.830	1.000	0.00416	48775	203
10	0.145	0.086	0.403	0.170	0.010	0.00001	48775	0
11	0.145	0.086	0.403	0.170	0.990	0.00084	58650	50
12	0.145	0.086	0.597	0.738	1.000	0.00548	48775	267
13	0.145	0.086	0.597	0.262	0.010	0.00002	48775	1
14	0.145	0.086	0.597	0.262	0.990	0.00192	58650	113
					Total:	***1.00000***	***Total:***	***32470***

Note that the values above only show the mean values of the distributions.

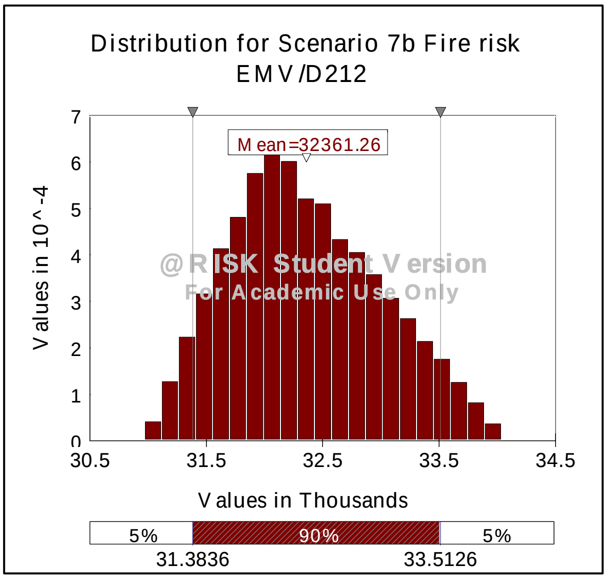
Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 30,987	5%	$ 31,418
Maximum	$ 34,296	50%	$ 31,601
Mean	$ 32,470	95%	$ 31,736
Std Dev	$ 691		

Scenario 7b: Sprinkler system, 1 hour FRR, dry type transformer								
Outcome event No.	**SDS**	**SS**	**FAT**	**MFF**	**WBI**	**Probability of each outcome**	**Consequence EMV (NZD$)**	**Risk NZD$/ fire incident**
1	0.855	0.914	-----------	-----------	1.000	0.78184	31000	24237
2	0.855	0.086	0.403	0.910	1.000	0.02701	47750	1290
3	0.855	0.086	0.403	0.090	1.000	0.00267	47750	128
4	0.855	0.086	0.403	0.090	0.000	0.00000	55300	0
5	0.855	0.086	0.597	0.887	1.000	0.03895	47750	1860
6	0.855	0.086	0.597	0.113	1.000	0.00496	47750	237
7	0.855	0.086	0.597	0.113	0.000	0.00000	55300	0
8	0.145	0.914	-----------	-----------	1.000	0.13213	30300	4004
9	0.145	0.086	0.403	0.875	1.000	0.00439	48775	214
10	0.145	0.086	0.403	0.125	1.000	0.00063	48775	31
11	0.145	0.086	0.403	0.125	0.000	0.00000	58650	0
12	0.145	0.086	0.597	0.783	1.000	0.00581	48775	283
13	0.145	0.086	0.597	0.217	1.000	0.00161	48775	79
14	0.145	0.086	0.597	0.217	0.000	0.00000	58650	0
					Total:	***1.00000***	***Total:***	***32361***
Note that the values above only show the mean values of the distributions.								

Simulation result from @Risk4.5



Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 30,976	5%	$ 31,384
Maximum	$ 34,042	50%	$ 31,550
Mean	$ 32,361	95%	$ 31,678
Std Dev	$ 643		

APPENDIX F: Calculation of the Cost Benefit Ratio

	[1] Existing risk, R_e (NZD\$) [1] Modified risk, R_m (NZD\$)	[2] Risk benefit R_B (NZD\$)	[3] Initial costs I_C (NZD\$)	[3] Annual costs A_C (NZD\$)	Interest rate, i	Useful life time, N (Year)	(P/A,i,n)	B/C ratio	Rank
Scenario 1 (Base case 1)	\$49,692	\$0	\$0	\$0	N/A	N/A	N/A	N/A	N/A
Scenario 2	\$49,692	\$0	\$806	\$0	7%	30	12.4	0.0	***9***
Scenario 3	\$49,334	\$359	\$3,106	\$0	7%	30	12.4	1.4	***8***
Scenario 4	\$48,616	\$1,077	\$3,648	\$0	7%	30	12.4	3.7	***6***
Scenario 5	\$47,988	\$1,704	\$6,307	\$0	7%	30	12.4	3.4	***7***
Scenario 6	\$32,516	\$17,177	\$12,000	\$850	7%	30	12.4	16.9	***1***
Scenario 7	\$32,516	\$17,177	\$12,806	\$850	7%	30	12.4	15.8	***2***
Scenario 8	\$32,485	\$17,208	\$15,106	\$850	7%	30	12.4	13.4	***3***
Scenario 9	\$32,423	\$17,269	\$15,648	\$850	7%	30	12.4	13.0	***4***
Scenario 10	\$32,369	\$17,323	\$18,307	\$850	7%	30	12.4	11.2	***5***
Scenario 4 (Base case 2)	\$48,616	\$0	\$0	\$0	N/A	N/A	N/A	N/A	N/A
Scenario 4a	\$47,964	\$652	\$8,100	(\$597)	7%	30	12.4	1.9	***1***
Scenario 4b	\$47,898	\$718	\$17,550	(\$1,743)	7%	30	12.4	1.7	***2***
Scenario 7 (Base case 3)	\$32,516	\$0	\$0	\$0	N/A	N/A	N/A	N/A	N/A
Scenario 7a	\$32,470	\$45	\$8,100	(\$597)	7%	30	12.4	1.0	***2***
Scenario 7b	\$32,361	\$154	\$16,550	(\$1,743)	7%	30	12.4	1.4	***1***

[1] Note that the estimated total risk of the base case is the existing risk, R_e, and the estimated total risk of the alternatives is the modified risk, R_m.

[2] Risk benefit is the difference between the existing risk, R_e and the modified risk, R_m.

[3] Initial costs, I_C, and annual costs, A_C, in the table indicate the cost difference from its respective base case; hence, when the required costs of alternatives are less then the costs of its respective base case, negative costs may result (as shown in the brackets).

* N/A – Not applicable

Blank Page