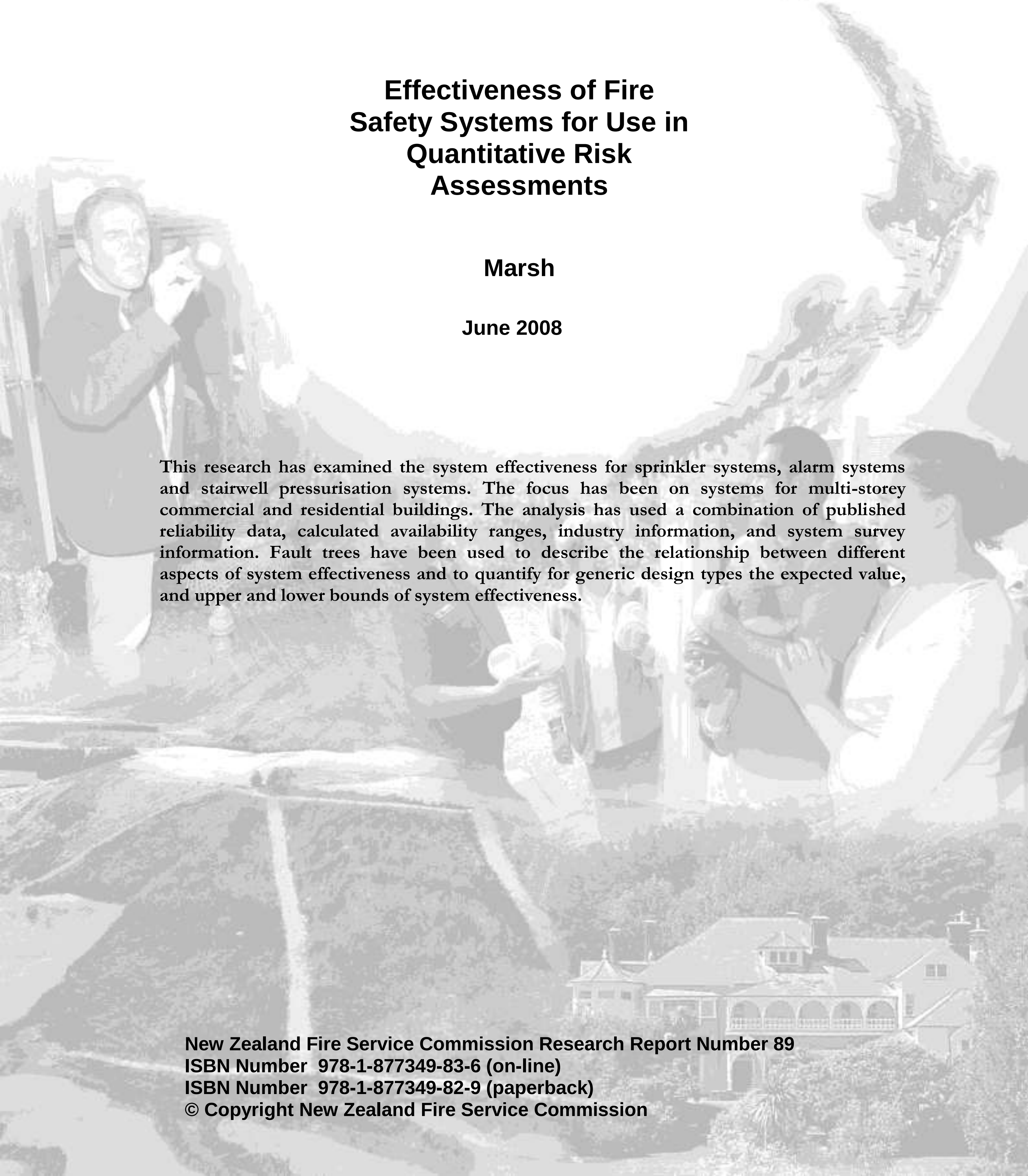
Fire Research Report



Effectiveness of Fire Safety Systems for Use in Quantitative Risk Assessments

Marsh

June 2008

This research has examined the system effectiveness for sprinkler systems, alarm systems and stairwell pressurisation systems. The focus has been on systems for multi-storey commercial and residential buildings. The analysis has used a combination of published reliability data, calculated availability ranges, industry information, and system survey information. Fault trees have been used to describe the relationship between different aspects of system effectiveness and to quantify for generic design types the expected value, and upper and lower bounds of system effectiveness.

New Zealand Fire Service Commission Research Report Number 89
ISBN Number 978-1-877349-83-6 (on-line)
ISBN Number 978-1-877349-82-9 (paperback)

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New Zealand Fire Service Commission

MARSH

MMC Marsh & McLennan Companies

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Version

Version	Release	Date	Author	Review
A	For milestone 1	10 July 07	NG	
B	Outline	28 September 07	NG	
C	With Discussion	3 October 07	NG	
D	Expanded	9 October 07		
E	Conclusions Added	10 October 07	NG	PJ
F	Executive Summary Added	12 October 07	NG	PJ
G	80% Draft	13 October 07	NG	PJ
H	With Sprinkler Surveys	16 October 07	NG	PJ
I	FPIS Survey Results	10 April 08	NG	
J	Revised Discussion and Structure	23 April 08	NG	EF
K	Incorporating Fazio Comments	23 May 08	NG	

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Executive Summary

System effectiveness has been examined for sprinkler systems, alarm systems and stairwell pressurisation systems. The focus has been on systems for multi-storey commercial and residential buildings.

The analysis has used a combination of published reliability data, calculated availability ranges, industry information, and system survey information. Fault trees have been used to describe the relationship between different aspects of system effectiveness and to quantify for generic design types the expected value, and upper and lower bounds of system effectiveness. Example fault trees are shown for reliability (for a simple stairwell pressurisation system) and effectiveness (for a town main sprinkler system in an apartment building). See appendices B and C for further fault trees.

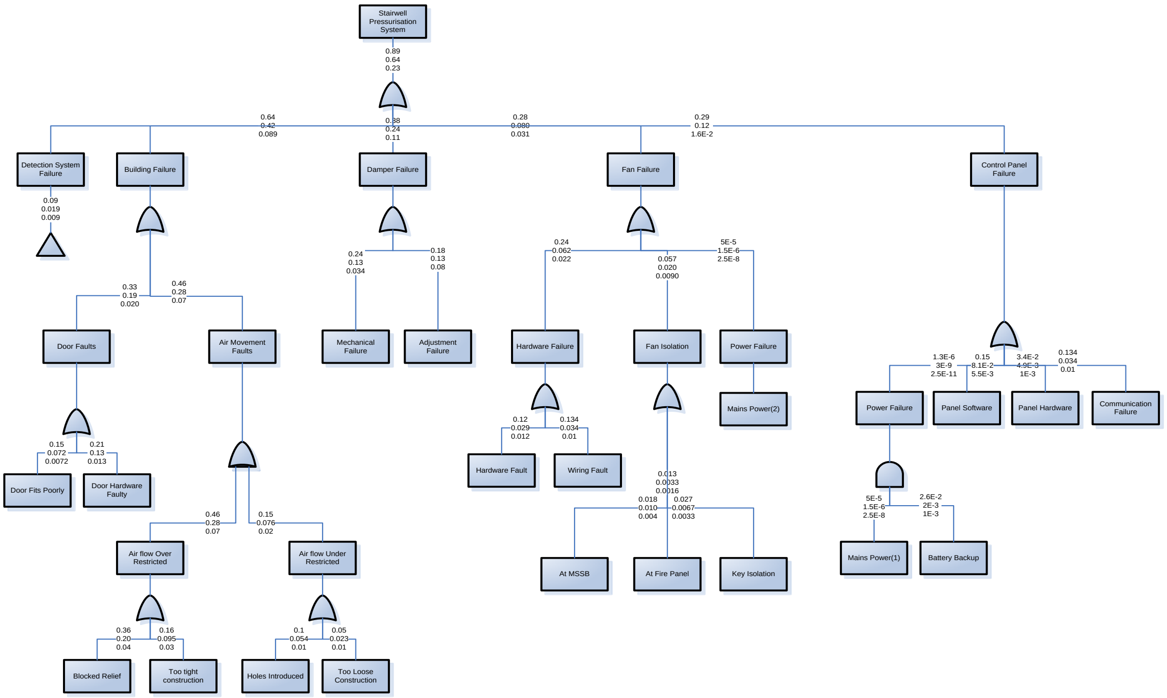
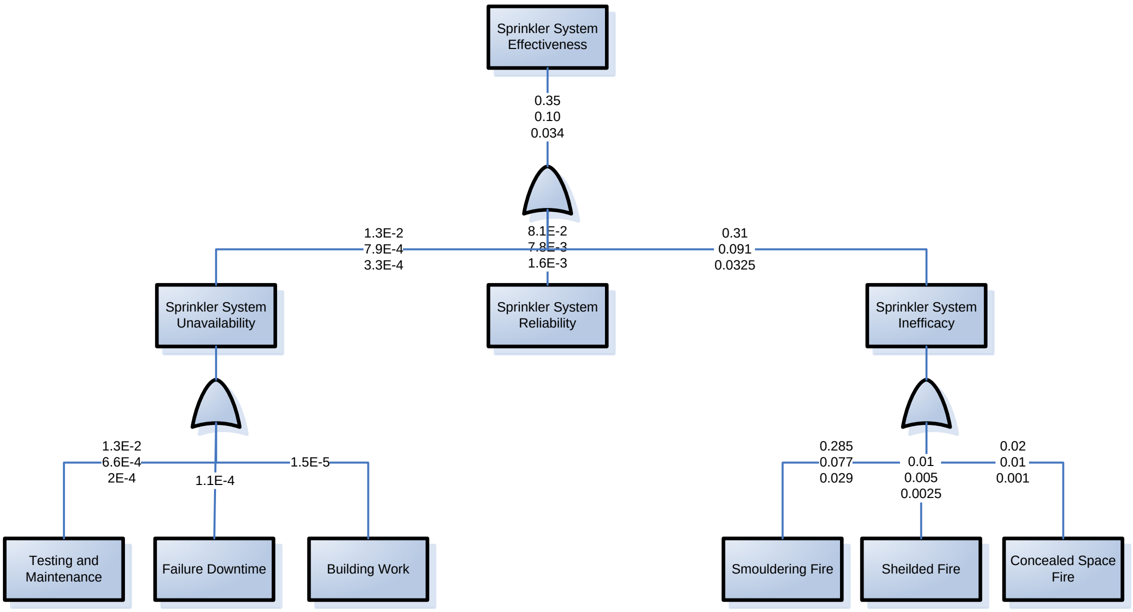


Figure 1.1: Simple Stairwell Pressurisation System Reliability

The numbers show the unreliability or ineffectiveness (subtract from one to get the reliability or effectiveness). The middle value of each triplet[1] of numbers is the expected or likely value, the top number is the upper bound (low effectiveness or reliability) and the bottom number is the lower bound (high effectiveness or reliability).



Towns main single supply
Auckland
Analogue Addressable Panel
Apartment

Figure 1.2: Towns Main Sprinkler System in an Apartment Effectiveness

Effectiveness of systems has been taken as a combination of the on-demand reliability, availability and efficacy.

Effectiveness has been analysed for the systems in isolation and has not explicitly included any aspect of response, evacuation and tenability time. However consideration of efficacy as a component part of system effectiveness has included consideration of certain fire scenarios (notably smouldering fires).

Efficacy is considered the likelihood that the system will operate as designed. A failure in efficacy is when a system does not operate at all or operate at a time in the fire where it can be reasonably considered that conditions would have become untenable. It is possible that if a quantitative risk analysis is being undertaken by an engineer that the efficacy value would be separated out from the other aspects of effectiveness to allow it to be separately identified within an event tree (for example).

Efficacy is a significant contributor to the overall effectiveness of sprinkler and alarm systems. Not surprisingly the overall effectiveness of these systems is reduced in design situations where a reasonable proportion of smouldering fires might be expected, particularly where for efficacy these fires need to be detected prior to any transition to a flaming stage. For example for sprinkler systems expected effectiveness varies from 90% to 95% dependent on the significance of smouldering fires in the scenario. Knowledge uncertainty (and natural variability) in the

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[1] Noting that in some cases only an expected value is given with no upper or lower bounds.

likelihood of smouldering fires introduces considerable uncertainty in the overall effectiveness of these system with effectiveness for sprinkler systems dropping below 80% if high frequencies of smouldering fires are assumed. Efficacy is difficult to determine for stairwell pressurisation systems given their complexity. Survey information used in the analysis implicitly includes efficacy as respondents were asked questions regarding system performance and the impact of failures on performance.

Availability has been considered to include testing and maintenance downtime, repair downtime and system isolation due to building work. The availability is generally small in comparison to efficacy and reliability but becomes significant in situations where reliability and efficacy are high. System availability for typical New Zealand sprinkler and alarm systems is estimated to be of the order of 99.8% to 99.9%. It does vary according to building type primarily due to potential for isolation with tenancy work.

Reliability varies depending on the system design. For sprinkler systems one potential area of unreliability is the communication of the signal to the evacuation system and also to the fire brigade. This was a significant contributor to reliability failure which has been regarded as a critical failure in the analysis though there is some justification for seeing it as a non critical failure dependent on the fire scenario. As would be expected sprinkler system reliability was relatively high, but significantly lower (order of magnitude) than the effectiveness value from Marryatt. Reliability for sprinkler systems was sensitive to the quality of testing and maintenance with the mechanical reliability (with change from well maintained to poorly maintained) decreasing from 99% to 83% (nominal values) for a typical diesel pump and tank system.

For alarm systems reliability was lower than for sprinklers with reliability being potentially reduced by system complexity. Expected reliability range for alarm systems is of the order of 88% to 98% depending on the complexity of the system. As for sprinkler systems the quality of testing and maintenance is key in achieving high levels of reliability.

Stairwell pressurisation system reliability is low (expected values of the order of 50%). This is due to the overall system complexity as well as industry opinion on the prevalence of faults on installed systems. There is considerable uncertainty in the data and also there is a large variation in the value of the effectiveness dependent upon assumptions regarding the quality of design, installation, commissioning and maintenance of the system.

Overall effectiveness for systems has been analysed for a number of assumed designs. The expected effectiveness values are summarised in table 1.1. These values are dependent upon a number of assumptions regarding the design, and also are subject to knowledge uncertainty as well as natural variability. It is recommended that they only be considered a first order estimate and for any design situation a specific analysis is undertaken using the relevant parts of this report and other sources. The values for stairwell pressurisation systems include faults with door hardware, construction details, and blocking of relief. If these factors are excluded (noting there is considerable uncertainty in the values of these factors) the reliability increases.

Distributions of effectiveness are presented in the body of the report based upon upper and lower bounds propagated through the fault tree. As with the expected values these should be considered first order approximations and adjusted values used for any design situation.

In the discussion the values obtained are compared with literature values and design vales and similarities and differences commented on. There are no fundamental discrepancies and when the various factors which influence values are considered there is consistency in the results presented with the body of literature.

Design Scenario	**Effectiveness [%]**
Sprinkler System Design	
Sprinkler System Office Building	95%
Sprinkler System Apartment Building	90%
Heat Detection System Design	
Simple office heat detection system	95%
Simple apartment heat detection system	90%
Complex office heat detection system	85%
Complex apartment heat detection system	80%
Smoke Detection System Design	
Simple office smoke (photoelectric) detection system	96%
Simple apartment smoke (photoelectric)detection system	88%
Complex office smoke (photoelectric)detection system	86%
Complex apartment smoke (photoelectric)detection system	78%
Simple office smoke (ionisation) detection system	97%
Simple apartment smoke (ionisation)detection system	93%
Complex office smoke (ionisation)detection system	87%
Complex apartment smoke (ionisation)detection system	82%
Stairwell Pressurisation System Design	
Fixed speed fan and barometric dampers	52%
Variable Speed drive system	47%
Variable Speed drive and motorised damper system	49%

Table 1.1: Summary of Expected Effectiveness for Typical Design Situations.

The use of quantitative risk analysis approaches has been discussed in the report and guidance given as to the use of event trees and fault trees in combination with the data presented.

The importance of commissioning and maintenance is highlighted with indications of the decline in system effectiveness if these regimes were to degrade from their current levels.

Trends in the approvals regime, in standards and technology are discussed in terms of the impact these may have on system effectiveness.

Structure

The remainder of the report is structured as follows:

Section 2. Introduction. To provide background material for the study and a frame of reference for the literature survey.
Section 3. Literature review. Published literature of fire system effectiveness.
Section 4. Role of Fire Risk Software. Brief discussion of fire risk software, how they handle effectiveness and their value in predicting effectiveness.
Section 5. New Zealand Statistics and Data Sources. New Zealand statistics, industry data and survey information on fire system effectiveness.
Section 6. Bias and Variation in the data/analysis. Discussion of bias, its causes and how to account for it. Including applicability to New Zealand and tends in the data.
Section 7. Analysing and Using the Effectiveness Data. Discussion on how effectiveness data can be described and used.
Section 8. Use of Effectiveness Information in Design Decisions. How effectiveness information can be used by designers to establish level of risk and compare design alternatives.
Section 9. Quantitative Risk Analysis. An overview of quantitative risk analysis approaches as they may be applied to fire engineering design.
Section 10. Assessing Fire Protection System. Main section of the report. Describes, collates and

analyses available information on reliability, availability and efficacy. Provides component and sub system reliability values and system availability and efficacy values.

Section 11. Discussion. Discussion of findings including comparison with literature.

Section 12. Conclusions.

Section 13. References.

2

Introduction

There is developing interest in the use of quantitative risk assessment (QRA) techniques as a method to support performance based fire engineering design. There are many reasons for this including concerns over the rigour of existing design methods, familiarity with QRA, and guidance documents and research supporting the use of QRA in fire engineering design.

The use of QRA allows objective comparison between ‘alternative’ and deemed to satisfy designs and has been used for this purpose in a number of Department of Building and Housing (DBH) determinations to help establish whether a particular alternative design provides an equivalent measure of life safety. QRA can also be used, in principle, to establish an absolute level of risk which can then be weighed against the risk tolerance. The establishment of life safety risk tolerance levels is a policy issue and one which, at present, is not clearly defined for design purposes in New Zealand.

QRA is a well established discipline with broad application in reliability engineering, loss prevention and financial risk. Of these areas it is loss prevention which has the strongest similarities to the characteristics of performance based fire engineering design though all three share common aspects.

Loss prevention is widely used in the process industries and is concerned with both prevention of loss of assets as well as loss of life or injury. Unlike fire risk in the built environment, for industrial life safety there are established tolerance levels (for example a threshold for an annual risk of loss of life) so absolute measurement rather than comparative performance is the normal approach. To allow this absolute assessment there is considerable effort applied to identifying the likelihood of the initiating event as well as characterising the consequences. For the built environment where comparative performance would be expected the likelihood of the initiating event may be less important depending on the fire scenarios of interest.

The broad framework for application of QRA is no different from any other risk assessment framework. For example it is entirely appropriate to use the AS/NZS 4360 process. Other methodology frameworks such as those provided in fire engineering guidance documents are consistent with this risk management approach.

In the process industries where QRA has been used for some time there is relatively rich data available on the risk of initiating fire and explosion events. This is in the form of a generic failure rate or event data as well as industry specific data; an excellent introduction to the subject is found in Lees (2005). Conventional fire protection systems (sprinklers, alarms) are used in the process industries but only form a relatively small part of the prevention and mitigation methods used. Building specific systems such as smoke management are extremely rare in process industries. Where building systems are present in the process industries they will often be in support buildings which will not generally be the highest risk either in terms of loss to the business or threat to life. Consequently the aspect of QRA specific to fire prevention systems is not as well defined as some other parts of QRA. Reliability engineering has QRA data for fire protection systems but not surprisingly this is focussed on failure rate in service.

There are many techniques available for undertaking QRA for life safety fire engineering design but for any of these it is generally necessary to establish the likelihood of the fire scenario of interest, the effectiveness of any mitigation measures, the vulnerability of people exposed, and the (range of) consequences of the fire.

Risk is the product of likelihood and consequence. For life safety this can be expressed for example as the likelihood of a loss of a life from fire in a particular building in a year. Knowing the likelihood of a fire event we can then use QRA methods to determine the likelihood of the outcomes from the fire and also their consequences. The distribution of likelihoods and consequences will depend to a significant extent on mitigation measures such as fire protection systems. Sprinkler systems for example will have a marked effect on the fire risk of a building [Williams et al. (2004)].

Establishing the consequence of fires including allowing for mitigation effects is not a trivial task but it does have the advantage that there are established methods and tools available to the designer. Considerable confidence in the predictions can be achieved with enough effort on defining the fire characteristics, the compartment characteristics, the tenability conditions as a function of time and location. Confidence can be improved further by use of sensitivity cases and of appropriately conservative parameters.

For many designs the effectiveness of fire protection systems is of critical importance. It can have a dramatic effect on the likelihood of various fire outcomes and thus on the measure of risk. Not only is it an important part of a meaningful QRA it is also relatively poorly defined. There is limited consensus on the quantification of effectiveness of fire protection systems and particularly on the likelihood of effective operation for a specific design case. The uncertainty in likelihood of system effectiveness may be so great that it completely distorts the risk assessment making the value of the use of sophisticated modelling of fire consequences highly subjective since there is a significant inconsistency in the level of confidence in the component parts of the QRA.

This can make assessment of the acceptability of the design extremely difficult. There is also a risk that use of poor information of the likelihood of system effectiveness could allow ill informed approval of designs which do not meet the expected level of life safety. As the sophistication of fire modelling increases it is inevitable (and appropriate in a performance based design environment) this will be used minimise fire protection requirements. Any increase in confidence in predicting the consequences of fire events needs to be matched by increasing confidence in our understanding of likelihoods in order to ensure the QRA is acceptably robust to give confidence to all stakeholders.

Overall system effectiveness can be considered to consist of the product of three components:

1. Functional effectiveness – will it perform adequately (meet performance requirements) for the fire scenario(s) of interest?
2. System Availability – will it be available (on-line) when called upon?
3. Operational Reliability – will the system operate when called upon?

Failure of any one of these will result in the system not being effective and therefore (generally) worsening fire consequences.

Functional effectiveness of systems is subjective. In reality there is a continuum of performance and often no clear pass/fail measure. When using QRA for fire engineering design the consequence analysis takes account of at least part of this uncertainty providing that fire scenarios are well defined and likelihoods of competing fire scenarios understood. It is possible systems may fail even when they are appropriate, due to natural variability. For example a fully compliant fire system may be unable to perform adequately because of an unusually rapid fire growth. By use of appropriate QRA techniques it is possible to allow for this uncertainty. The uncertainty introduced by natural variability is distinct from uncertainty due to lack of knowledge which will be discussed separately.

Functional effectiveness is highly dependent on the design basis for systems. It is vulnerable to design process error, installation quality, unforeseen or modified performance requirements, and (particularly for complex systems) poor commissioning.

In comparison to functional effectiveness system availability is relatively straightforward. In some large buildings complications can be caused by the frequent partial impairment for modification and maintenance. This can be readily accounted for within the QRA. A special case of availability is consideration of system availability following an earthquake or explosion event.

Operational reliability is well understood. When reported it may implicitly include availability. Reliability of systems is highly dependent on testing, maintenance and monitoring (Lees).

Availability and operational reliability are not subject to natural variability in the same sense as functional effectiveness. They will of course vary in terms of observed reliabilities relative to predicted reliabilities.

All of the measures are subject to knowledge uncertainty. In some cases this uncertainty is unknown and not represented. In some cases uncertainty is accounted for by providing confidence limits on the reliability value. Alternatively reliability distributions are used to account for uncertainty.

The term reliability is commonly used in a number of ways when discussing fire protection systems:

- It is often used when discussing the likelihood the system will activate when called upon (i.e. the likelihood of system availability × the likelihood of system operation or in some cases simply the likelihood of system operation). This will be referred to as *operational reliability*.
- It is used when discussing the overall fire system effectiveness (i.e. the likelihood of functional effectiveness × the likelihood of system availability × the likelihood of system operation). The term *system effectiveness* will be used for this measure.
- The reliability of component parts of systems to operate when required, for example fire pump start-up on demand. This will be referred to as *on demand reliability*.
- The ability of systems or components to function as required for a given time under given conditions, this will be referred to as *service reliability*.

3

Literature Review

The literature review covers effectiveness of fire protection systems which includes consideration of research covering the following:

- Component reliability (both ‘in service’ and ‘on demand’)
- Overall system reliability (‘on demand’)
- Availability of systems
- Efficacy of Systems
- Research into the overall effectiveness (combination of reliability, availability and effectiveness) of systems. Including industry studies as well as fire service injury and fatality statistics.
- Use of models (primarily fault trees) as a method to analyse and derive system effectiveness measures
- The use of QRA approaches applied to fire engineering.

Reliability of System Components

In Service Reliability

Much of the historical data available for the process industries is in service reliability data. This is data providing a measure of the risk of component failure whilst in service. A typical example would be a motor failing to run. Many components or combinations of components have multiple failure modes some of which may be relatively benign. Fire systems consist of a mixture of components some of which are in constant service others which only operate (or change their state) under fire conditions. Whilst in service reliability may not apply to all fire system components it is of interest for the following four reasons:

- Some components are in constant service and in service reliability provides a directly useful measure.
- Service reliability provides an insight into prudent maintenance requirements that should appear on the compliance schedule of systems.
- From a known maintenance regime and information on likely time of repair it is possible to **estimate** availability of components.
- From the maintenance regime and knowledge of critical failure modes it is possible to **estimate** the failure on demand (operational reliability).

The reliability R [hr^{-1}] of an in service component (with constant fault rate) is related to the failure rate λ [hr^{-1}] and the maintenance interval t [hr] by the expression (Lees):

$$R = e^{-\lambda t} \tag{1}$$

Decreasing the maintenance interval increases the expected reliability of the system or component. The probability of failure P_{FM} over the maintenance cycle is then given by (Lees) :

$$P_{FM} = 1 - R \tag{2}$$

Knowing the time to repair a fault [hr] the availability, A [-] can be estimated from:

$$A = 1 - \frac{P_{FM}t}{8766} \tag{3}$$

Let us assume a constant fault rate for a fire protection system and further assume that the maintenance and testing regime is thorough, such that it would be expected to uncover and correct any faults which have occurred over the maintenance period. In this case the probability of failure on demand (operational failure) can be approximated by:

$$P_{FO} = \frac{\lambda t}{2} \ [\text{hr}^{-1}] \tag{4}$$

The above expressions for availability and the probability of failure assume that the maintenance and testing process does not introduce errors. Lees reports that a balance needs to be achieved between the benefits of maintenance in terms of fault identification and the potential for the maintenance activity to introduce new faults.

Data from the offshore oil and gas industry is given in the OREDA database (http://www.sintef.no/static/tl/projects/oreda/.) Examples of selected data are given in Table 3.1.

System	**Failure rate per 10^6 hours**[2]			**Mean Repair Time [hours]**
	Lower	**Mean**	**Upper**	
Ionization Smoke Detector	1.6	4.6	7.6	4.5
Photo Electric Smoke Detector	-	2.13	-	3.3
Rate of rise heat Detector	1.1	3.6	6.4	5
Fire panel (Critical)	15	48	84	10
Fire panel (All modes)	27	140	250	12
Diesel Fire Pump (Critical)	120	210	310	86
Diesel Fire Pump (All modes)	680	840	1000	81
Electric Fire Pump (Critical)	24	72	170	130
Electric Fire Pump (All modes)	120	210	340	51
Deluge Valve (Critical)	2.8	5.8	9.4	8
Deluge Valve (All modes)	12	21	31	8.5
Fans (Critical)	18	26	35	16
Fans (All modes)	42	60	79	14
Dampers & Actuators (Critical)	0.73	8	16	13
Dampers & Actuators (All modes)	6.6	20	34	13

Table 3.1: OREDA reliability data

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[2] Calendar time, operational time significantly shorter for many of these items.

The upper and lower confidence bounds on the OREDA data represent the 90% confidence interval on the data. For some devices failures modes are described as critical or all modes. Critical indicate that the device would cease to function safely (fail dangerous), all modes includes fail-safe and false alarm modes of failure.

Gupta (1984, 1985) analysed failure rates for ionisation smoke detectors in a hospital environment. The failure rates are summarised in Table 3.2.

Failure Rates [1/a]		
Safe	**Dangerous**	**False Alarm**
7.0E-5	3.0E-5	8.0E-4

Table 3.2: Ionisation Smoke Detection Failure Rate (Gupta)

Steciak and Zalosh reported smoke detector malfunction rates at 1.2E-6/hr which is similar to the lower bound of the OREDA data. This perhaps being in part due to the challenging environment of the smoke detectors in the offshore environment.

Gupta also gave alarm panel failure rates of 6.8E-6/hr. This is substantially lower than the OREDA data.

Steciak studied Halon system reliability in computer rooms. The associated mains power failure rate was 4.75E-6/hr. From Lees battery failure rate is given as 3E-6/hr.

Damper failure can occur for a number of reasons. The duct can collapse or obstruct Lees gives a failure rate for this mode of failure as 1E-6/hr. A number of authors including Lees estimate failure of a damper to activate as 6.6E-3/hr which is several orders of magnitude higher than the OREDA data. Steciak estimates the failure of the damper to activate correctly as 3E-3/hr.

Smoke system component reliabilities from Hobson and Stewart (1972) are provided in Table 3.3.

Item	Failure Rate	Estimated Life [years]
Axial fan – fan Axial fan – motor Overall	0.002 0.050 0.052	15 – 20
Centrifugal fan – fan Centrifugal fan – motor Overall	0.250 0.250 0.500	15 – 20
Pneumatic controls	0.680	15

Table 3.3: Reliability data for smoke system components (Hobson and Stewart)

Nash and Young presented a range of component failure rates for sprinkler system components, summarised in Table 3.4.

Component	Failure Rate [failures/year]
Wet alarm valve	0.4×10^{-4}
Accelerator	7.9×10^{-3}
Main sprinkler stop valve	2×10^{-3}
Non return valves	10×10^{-3}
New sprinklers	3.1×10^{-2}
Old sprinklers	5.1×10^{-2}

Table 3.4: Reliability data for sprinkler system components (Nash and Young)

Rönty et al (2005) give summary reliability data for a number of sprinkler system components based upon 12 years of Finnish statistics. These are summarised in Table 3.5.

Component	Failures	Exposure [device years]	Failure Rate [1/a]		
			Minimum	Point	Maximum
Town Main	3	2137	2.6E-4	1.0E-3	2.5E-3
Storage Tank	0	353	NA	NA	6.5E-3
Pressure Tank	1	51	1.0E-3	2.0E-2	9.3E-2
Alarm Valves	10	8300	6.5E-4	1.2E-3	2.0E-3
Pipe Array	38	11600000[3]	2.4E-6	3.3E-6	4.3E-6
Sprinkler Heads	577	3490000	1.5E-4	1.7E-4	1.8E-4
Diesel Driven Pump	13	889	8.7E-3	1.5E-2	2.3E-2
Electrical Driven Pump	5	809	2.5E-3	6.2E-3	1.3E-3
Sprinkler Installation	42	4013	8.0E-3	1.1E-2	1.4E-2

Table 3.5: Sprinkler System Component Reliability Data (Rönty et al.)

The reliability of town main water supplies was estimated by Feeney (2001). The figure for Auckland city based on data between1997-2000 was 7E-5/yr. For Melbourne 6E-5/yr. Zalosh (2003) presented a value calculated for reliability using a fault tree analysis of 3.6E-4/yr.

Frequency of pipe break data has been presented by Zalosh for a number of cities most of these are in the United States. Frequency of pipe breaks is a function of pipe diameter, pipe material, age of pipe, and ground conditions.

On Demand Reliability of Components

On demand data is available where failure performance has been monitored or measured for a known number of demand events, as with in service reliability there can be various failure modes of varied severity. Some data presented is based on ‘real system’ performance (such as the OREDA data) others are from experimental studies.

OREDA on demand data for fire pumps and deluge valves is presented in Table 3.6, lower and upper values represent the 90% confidence limit in the data.

Component	Reliability on Demand		
	Lower	Expected	Upper
Diesel Fire Pump	87%	95%	99.96%
Electric Fire Pump	97.9%	99.33%	99.88%
Deluge Valve Set	94.8%	99.0 %	>99.9%

Table 3.6: OREDA Failure on Demand Data

In the work of Feeney the reliability of a diesel pump supply is estimated as 88% for a poorly maintained diesel pump and 99.85% for a well maintained diesel pump.

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[3] Exposure is length (m) years, failure rate is per metre per year.

Grosse et al (1996) reported on detector failure probabilities. Values are summarised in Table 3.7.

Detector Type	**Probability of Failure on Demand**	
	Smouldering Fire	**Flaming Fire**
Ionisation	55.80%	19.80%
Photoelectric	4.06%	3.99%
Fusible link	99.90%	1E-6%

Table 3.7: Detector Failure Probabilities

NRCC presented a range of failure on demand data from a variety of sources including Lees.

Component	**Probability of Failure on Demand**		
	Lower bound	**Point estimate**	**Upper bound**
Sprinkler Heads Fail to Open		<1E-6	
Fire Detectors Fail to Function	1.89E-3	2.97E-3	4.45E-3
Deluge Valves to Open	8.9E-4	1.9E-3	3.58E-3
Fire Pumps Fail to Start	4.47E-3	1.4E-2	2.39E-2
Check Valves Fail to Open	3E-5	1E-4	3E-4
Alarm Valves Fail to Function	2.68E-2	3.62E-2	4.81E-2
Personnel Fail to Trip Manual Device		0.2	
Valves Close Inadvertently	5.47E-3	5.47E-2	0.547

Table 3.8: Failure Rate Data

Peacock, Kamath and Keller (1982) studied detector performance in industrial buildings (Table 3.9). The high failure rates for heat detection may be due to fires being too small to operate the detector.

Detector Type	**% failure**
Smoke	8.5
Heat	20

Table 3.9: Detector failure rates (Peacock et al.)

Rose-Pehrsson et al. (2003) reported on experimental studies comparing performance of a number of detector types including ionisation, photoelectric, multi-sensor and a number of prototype detectors utilising neural network technology. A number of fire types were tested including a number of nuisance fires, smouldering fires and flaming fires. Some genuine fire types were unable to be detected by any of the detectors including smouldering cables and overheated circuit boards. This particular result was not in itself surprising. The sample size was relatively small, 39 fires and nuisance events in total.

The summary results from the study were as shown in Table 3.10 for the photo, ion and combination detectors:

Detector Type	**All Fires**	**Flaming Fires**	**Smouldering Fires**
Simplex ION	66.7%	92.3%	42.9%
Simplex Photo	74.1%	84.6%	64.3%
Combination	77.8%	92.3%	64.3%

Table 3.10: Detector Response (Rose-Pehrson et al.)

Milke (1999) measured 97% simplex detector performance for flaming fires and 25% for smouldering fires.

Operational Reliability

Reliability depends on the potential for a system to fail on demand. It is analogous to the research presented for on-demand reliability for system components. For detection systems the operational reliability of the system will be highly dependent on the on-demand reliability of detectors. For sprinkler systems the detectors themselves are less important and operational reliability is impacted by factors such as the water supply. Smoke management systems being complex would be expected to have their operational reliability be dependent on the interactions of the on-demand reliability of the component parts which is the approach used by Zhao when estimating reliability of smoke pressurisation and zone control systems using fault tree techniques.

Generally speaking the literature data on system effectiveness (overall reliability) does not identify the relative importance of efficacy, availability and operational effectiveness. The relative importance will vary depending of the sample type and the method of analysis. For some data the reported figures are probably close to the system operational reliability, for example the figures from Marryat would be expected to be close to these values given high system availability and controls on design, installation and commissioning.

For sprinkler system Watanabe gave system operational reliability of 98.9%. Thomas et al (1992) estimated operational reliability as 98.1%.

Röwekamp et al. (1997, 2000) referenced in Nyssönnen et al. compared a number of German alarm data sets (4 in the nuclear industry and one outside of the nuclear industry). These are summarised in Table 3.9.

Study	**System Failure on demand**	**Operational Reliability**
German BWR	1.27E-3	99.87%
German PWR1	4.22E-4	99.96%
GAL (1980)	9.00E-2	91%
GRS (1985)	4.00E-3	99.6%
German non nuclear data	7.90E-2	92.1%

Table 3.11: On Demand (operational) Reliability for Alarm Systems (Röwekamp et al.)

Nyssönnen et al reviewed critical failure frequency of alarm system components (non nuclear installations) and from this derived latent failures on demand (the breakdown corresponded to a fault tree structure proposed by the authors).

Failure type (Fault Tree Element)	**# Failures**	**Latent Failures per demand**		
		Minimum	**Point**	**Maximum**
Critical failure in control unit (2)	22	9.4E-4	1.3E-3	1.8E-3
Initiating circuit fault (3.2)	188	8.3E-4	9.4E-4	1.1E-3
Initiating circuit signalling fault (3.2)	110	4.7E-4	5.5E-4	6.4E-4
Failure in announcement forwarding (3.3)	48	2.2E-3	2.8E-3	3.6E-3
Announcement forwarding disconnected (3.3)	187	9.7E-3	1.1E-2	1.2E-2
Initiating circuit disconnected (3.4)	118	5.1E-4	5.9E-4	6.8E-4

Table 3.12: Demand Failures for Alarm System Components (Nyssönnen et al.)

Nyssönnen et al also presented statistics for non critical failures for example failure of fault signalling which in itself would not prevent alarm from operating but would compromise the reliability of the system over time.

Operational reliability for alarm systems and smoke management systems can, in principle, be estimated from on-demand reliabilities of component parts.

System Availability

System availability is (in principle at least) a simpler parameter to determine than efficacy.

Sprinkler system availability depends primarily on the availability of the water supply. This may be unavailable due to unavailability of the towns main, or because the system is isolated. The main reasons for isolation would be extensions or modifications being undertaken on the system or for valve overhauls.

Japanese studies (Watanabe) give an availability figure of 99.3%, in terms of unavailable hours per year this is 61 hours per year.

This figure is high compared with estimates for a typical simple residential occupancy type system. For this system one might expect to allow 2 hours every 4 years for the valve overhaul and 2 hours per year (on average) for maintenance work requiring system isolation.

Retail (and to a lesser degree office) occupancies would be expected to have significantly higher isolation frequencies.

Alarm system availability from Watanabe is 97%.

No specific data was found for smoke detection system or smoke management system availability.

Efficacy

Efficacy is a measure of the performance of the system in its design situation. Literature in this area is focussed on system performance rather than system components an exception being the work of on the efficacy of sounders by Thomas (2008) that showed that different signal types at the sounder resulted in different performance as measured by waking effectiveness.

The efficacy (functional effectiveness) of fire protection systems is to a large degree controlled by a process of testing, listing and standards. Testing determines the performance of the system against some benchmark measure, listing proscribes specific limitations in the use of the system, and standards ensure that systems are designed, installed and maintained to achieve an acceptable standard of performance.

Sprinkler Systems

For sprinkler systems the normal performance measure is that they control the fire (or suppress it in the case of suppression mode sprinklers). This in turn provides the required property protection or life safety performance for the design. For some situations such as high challenge fires or residential sprinklers specific testing is used to confirm the specific performance. For other situations sprinklers may be accepted on a simple basis of water distribution and density.

In general for sprinkler systems functional effectiveness is considered to be high. A Japanese study (Watanabe 1989) reported functional effectiveness for sprinkler systems of 99.9%. The reported overall system reliability in the New Zealand Sprinkler Standard (2003) is given as 99.5% which implies a functional effectiveness of better than 99.9%. Data exists from NFPA (Anon.) on the probability of opening a certain number of sprinkler heads. This is not entirely a measure of functional effectiveness as an excessive number of heads may open due to faults with the system or poor operational procedures however it does provide another guideline. If it is assumed that 20 (or greater) sprinkler operation represents functional failure then the probability for wet pipe sprinkler systems is approximately 99.5% which is consistent with the other references.

None of the research considers the specific relationship of sprinkler system parameters on functional effectiveness. Intuitively it would be expected that increasing water density would increase the probability of effective control or suppression but no quantification of such a relationship in the literature has been discovered. What can be found in the literature is testing results indicating failure when the density is reduced too low (notably the halt on the trend towards lower and lower densities for residential sprinklers). Likewise other testing results provide qualitative insight into the relationship between functional effectiveness and parameters such as ceiling height.

The performance of systems is also a function of the fire scenario. Research exists which considers the functional performance of sprinkler systems for fire scenarios with low heat release rate fires. The work of Shelley (2004) considers the functional performance of sprinklers with a domestic television set fire as the fire scenario. The results demonstrate (at a qualitative level) that functional performance of sprinkler systems is highly dependent on both the fire scenario and the design objectives. Out of the 20 recorded tests the sprinkler failed to activate on 5 occasions.

In summary for sprinklers the functional effectiveness is high providing the following criteria are met:

- The fire scenario is representative of the occupancy.
- The fire is not shielded.
- The fire is not a smouldering fire.

Fire Alarm Systems

For alarm systems the performance measure is that they detect the fire in a timely manner to allow for evacuation of the building and/or fire brigade response. Testing of systems is against reference fires and acceptable performance is based on reliable detection within a certain time.

A Japanese study (Watanabe) reported functional effectiveness for alarm systems of 93.9%. Functional effectiveness being measured by the ability of the detector to respond to the fire within the required (standard) time.

Similar to sprinkler systems the performance of alarm systems is a strong function of the fire scenario. The functional performance is primarily dependent on the detector response to the fire signature with different detector types relying on different characteristics of the fire for their operation.

Significant comparative work has been undertaken looking at the response of different detector types (ionisation type, optical type, carbon monoxide, etc) for example the work of Rose–Pehrsonn et al. summarised in Table 3-10. This work indicates functional effectiveness of detector type for different categories of fire scenario.

The work of Rose-Pehrsonn et al., also indicated that multi-sensor detectors in principle provide better functional performance as they allow for appropriate sensitivity levels on each sensor type. The main benefit shown from this study however was their improved nuisance alarm performance as opposed to their ability to detect genuine fires.

Waking effectiveness to detectors is also a critical characteristic when comparing functional effectiveness of systems which simply alert to systems such as sprinklers and smoke management which maintain tenability. Duncan (1999) measured waking effectiveness to domestic smoke detectors as 89%, the success criteria being based upon response times to the alarm. Based upon this work and other studies Palmer (1999) adopted a waking effectiveness of 90% for smoke detection systems.

Shelley's work showed comparable performance between ionisation and photoelectric detectors (optical detectors being somewhat slower to respond) when exposed to a television fire scenario. Reliability between the two in terms of response to the fire was essentially the same with no recorded failures to activate and ASET >>RSET .

In summary for alarm systems the functional effectiveness is highly dependent on the design basis and fire scenario. Specifically the selection of a detector type suitable for the fire signature of interest.

Smoke Control

Smoke control system performance is highly specific to the design of the system and the fire scenario. Qualitative references [Loveridge(1998)] are made to the danger posed by smouldering fires where there is insufficient heat to operate a detector but no quantification of the significance of these was found in the literature.

Functional effectiveness of these systems depends on the design basis, quality of installation and commissioning. The importance of these factors are referred to by a number of authors including Zhao (1998), Fazio (2004), and Ferreira (2005).

The narrow range of operation of smoke pressurisation systems with a typical minimum 20Pa to maximum 80Pa leads to a need for sectioning of stairwells (for heights greater than approximately 30m). This can be extended by specific pressurisation design methods see for example Jensen (2003).

Human Response Factors

In the broadest sense the overall efficacy of the 'system' includes human response. In terms of awareness of and response to fire cues (including system generated cues). This broad approach is clearly part of the fire engineering design process (and would typically be included in the QRA for example by inclusion in any event tree) but has not been considered here to be part of the fire protection system efficacy. However for completeness some discussion is included of the occupant response.

The effectiveness of cues is a function of the occupant characteristics notably:

- Asleep or awake
- Incapacitated by drugs or alcohol
- Age of occupant
- Whether children present in room

For selected occupant groups Hasofer et al (2007) reports the following probabilities of cue recognition. Two sets of probabilities are presented, the first for awake occupants and the second for sleeping occupants.

Cue	Adults	Children Present	Elderly Occupants
Light Smoke	1.00	1.00	1.00
Local Alarm	0.99	0.99	0.95
Corridor Alarm	0.78	0.78	0.72
EWIS	0.9	0.9	0.9
Warning	1.00	1.00	1.00
Staff Instruction	1.00	1.00	1.00

Table 3.13: Probability of Cue Recognition for Occupants Awake (Hasofer et al.)

Cue	Adults	Children Present	Elderly Occupants
Light Smoke	0.10	0.07	0.10
Local Alarm	0.98	0.66	0.91
Corridor Alarm	0.73	0.49	0.67
EWIS	0.80	0.60	0.80
Warning	1.00	1.00	1.00
Staff Instruction	1.00	1.00	1.00

Table 3.14: Probability of Cue Recognition for Sleeping Occupants (Hasofer et al.)

The probability of cue recognition for incapacitated occupants has been taken as 0.0 for all cases.

Given cue recognition the conditional probability of action depends on the location of the fire. Where the compartment is the room of fire origin it is assumed that probability of evacuation is 1.0. Where the compartment is not the room of fire origin but is within the fire/smoke cell of origin (for example a kitchen fire in an apartment where the occupant in receipt of the fire cue is in the bedroom) the probability of locating fire as the primary action has been taken as 1.0.

For cases where the occupant is outside of the smoke/cell of origin (for example a neighbouring apartment, separate office tenancy) then the probability of three basic **initial** activities (evacuate, investigate and wait) has been taken as conditional on the nature of the fire cue. Probabilities are summarised in table 3.15.

Cue	Investigate	Start Evacuation	Do nothing (wait)
Light Smoke	0.50	0.00	0.10
Local Alarm	0.80	0.10	0.10
Corridor Alarm	0.28	0.12	0.60
EWIS	0.05	0.90	0.05
Warning	0.0	1.00	0.0
Staff Instruction	0.0	1.00	0.0

Table 3.15: Initial Action Following Fire Cue

Overall System Reliability (Effectiveness)

Literature on overall system reliability (effectiveness) comes from two main sources. Studies of fire service statistics and specific industry studies. There are also values used for design purposes or recommended by practitioners which are based on expert opinion being applied to the available literature.

The need for the use of engineering judgement (due to the lack of robust or broadly applicable datasets) in assessing effectiveness of fire protection systems is acknowledged. For example the Electric Power Research Institute (2005) in their methodology document for probabilistic risk assessment for fire in nuclear facilities take the approach that expert judgement be used in estimating fire protection system effectives with the compliance with recognised standards being a significant weighting factor in the decision.

Fire Alarm Systems

Bukowski, Budnick and Schemel (1999) reviewed the literature on fire detection system reliability. They reported the work of Hall (1995) on smoke detection. The summary reliability estimates from Hall are presented in table 3.16 below:

Occupancy	Property Use	Mean Reliability [%]	95% Upper Confidence Level	95% Lower Confidence Level
Residential	Apartments	69.3	69.9	68.7
	Hotels/Motels	77.8	79.3	76.4
	Dormitories	86.3	88.4	84.3
Commercial	Public Assembly	67.9	69.8	65.9
	Stores & Offices	71.7	73.5	69.9
	Storage	68.2	70.0	66.3
	Industry & Manufacturing	80.2	81.3	79.1
Institutional	Care of Aged	84.9	86.6	83.3
	Care of Young	84.0	86.3	81.6
	Educational	76.9	79.6	74.1
	Hospitals & Clinics	83.3	85.4	81.2
	Prisons & Jails	84.2	85.9	82.5
	Care of Mentally Handicapped	87.5	90.3	84.8

Table 3.16: Smoke Detection System Reliability (Hall)

The same authors also reported on four reliability studies, the Warrington Delphi group study from the UK, the expert opinion values published in the Australian fire engineering design guidelines document and two Japanese studies based upon incident data. The results from these (% likelihood of success) is summarised below in Table 3.17:

System	Warrington Delphi Group		Australian Fire Engineering Design Guidelines			Japanese Incident Data Studies	
	Smouldering	Flaming	Smouldering	Flaming	Flashover	Tokyo FD	Watanabe
Heat detector	0	89	0	90	95	94	89
Home Smoke Alarm	76	79	65	75	74	NA	NA
System Smoke Detector	86	90	70	80	85	94	89
Beam Smoke Detector	86	88	70	80	85	94	89
Aspirated Smoke Detector	86	NA	90	95	95	NA	NA

Table 3.17: Summary of Detection System Effectiveness (in Bukowski et al.)

Duncan and Wade (2000) noted that reliability of smoke alarms fell in the range 60% to 90% a value of 74% was used in the event tree models they developed.

Enright (2003) assumed a smoke detector reliability of 90% based on UK data (referenced from BS DD240 this figure is also quoted for heat detector reliability). This is at the upper end of the range of published values. A normal distribution was assumed with a relatively small standard deviation of 0.2, giving a 95% confidence interval of 86% to 94%.

Wade and Page (2006) reference the work of Houlding and Rew (2003) for the detection system reliabilities used in their work. The figures referenced from Houlding and Rew are themselves derived from Hall and the Warrington Delphi Group Study. Wade and Page then use a symmetrical PERT distribution for fire detection system success with a minimum of 70%, expected value of 80% and a maximum of 90%. Houdling and Rew also referenced the BS DD40 data used by Enright giving a value of 76% for heat detector reliability

Guymer and Parry collected data from various US nuclear power plants in the 70's and 80's. Based on this study the estimated smoke detector reliability was 91% and heat detector reliability was 87%.

Ruegg and Fuller (1984) estimated smoke alarm reliability to be 85%.

Gwynee (2007) reported on the work of Purser and Kuipers who investigated 91 incidents (predominantly residential). Smoke detectors were present in 62% of the cases. Where they were installed they activated 51% of the time and once activated they were effective 40% of the time. The data indicated that hearing the alarm was reported as the mechanism they became aware of the fire for less than 10% of people involved. This seemed to be the case regardless of whether they were in the room of origin or outside of the room of origin. In the former case the most common reason people became aware was because they saw flame or heard a noise (relating to the fire), these two accounted for around a thirds of the cases where people were in the room of fire origin. It is not clear what proportions of these cases had detectors in the room of fire origin. For people outside of the room of origin the single most common mechanism was being told by others. Discounting this, the next most common mechanism was seeing or smelling smoke, or hearing the fire. These accounted for around 40% of all cases.

Ahrens (2007) reviewed alarm system performance in the US based on 2000 to 2004 statistics. Across all residential occupancies the fire was recorded as too small to operate the detector in 5% of cases, to fail to operate in 7% of cases. Two other categories were no smoke alarm present and if smoke detector alerted occupants with % of 24% and 15% respectively. Failure allocated to these causes may not be due to any reliability issue with the detector. For apartment fires 4% of fires were too small to operate, 5% were failure to operate, 11% were not present and 15% were where the detector did not alert occupants.

Watson et al (2002) reported on Scottish statistics from 1994 to 2000. The number of fires where a smoke detector was present was reported as 30,961. For 57% of cases the detector operated and was effective, for 11% the detector operated but was ineffective (giving an operational reliability of 68%) for the remaining 32% of incidents the detector was recorded as not operating.

NFPA 72: 2007 the Alarm system standard has assumed reliability as described below:

From NFPA 72:2007

2) *Reliability of fire alarm systems. Fire alarm systems located in dwelling units and having all of the following features are considered to have a functional reliability of 95 percent:*
   - *(a) Utilizes a control unit*
   - *(b) Has at least two independent sources of operating power*
   - *(c) Monitors all initiating and notification circuits for integrity*
   - *(d) Transmits alarm signals to a constantly attended, remote monitoring location*
   - *(e) Is tested regularly by the homeowner and at least every 3 years by a qualified service technician*

(3) *Reliability of fire alarm systems without remote monitoring or with wireless transmission. Fire alarm systems for dwelling units with all of the preceding features except (d) or systems that use low-power wireless transmission from initiating devices within the dwelling units are considered to have a functional reliability of 90 percent.*

(4) *Reliability of other systems. Fire alarm systems for dwelling units comprised of interconnected smoke alarms where the interconnecting means is monitored for integrity are considered to have a functional reliability of 88 percent. If the interconnecting means is not supervised or the alarms are not interconnected, such systems are considered to have a functional reliability of 85 percent.*

Sprinkler Systems

From the Tokyo Fire Brigade Data collected between 1987 and 1996 and analysed by Yoshiro (1987 – 1996) automatic sprinkler system reliability was assessed as 97.2%.

Sprinkler system reliability was studied by Rashbash (1975) and based upon UK fire data between 1966 and 1971 a reliability of 86% was obtained. The value for Australia and NZ from NZS 4541 is 99.5%. The large discrepancy is due in part to the difference in failure criteria between the two studies. Miller (1977) using FM system data reported a mean reliability of 91%.

Bukowski, Budnick and Schemel (1999) reviewed the literature on fire sprinkler system reliability. They reported three reliability studies, the Warrington Delphi group study from the UK, the expert opinion values published in the Australian fire engineering design guidelines document and a Japanese study based upon incident data from the Tokyo Fire Department. The results from these (% likelihood of success for a number of performance outcomes) is summarised below in Table 3.18:

System Performance	**Warrington Delphi Group**	**Australian Fire Engineering Design Guidelines**			**Japanese Incident Data Studies**
		Smouldering	**Flaming**	**Flashover**	**Tokyo FD**
Sprinklers Operate	95	50	95	99	97
Sprinklers Control but do not extinguish	64	NA			NA
Sprinklers Extinguish	48	NA			96

Table 3.18: Sprinkler System Effectiveness (in Bukowski et al.)

The same authors also collated sprinkler system reliability data for a large number of reported studies. These are summarised in Table 3.19 below grouped by occupancy type:

Occupancy	**Reference**	**Reliability Data**
Commercial	Milne [1959]	96.6/97.6/89.2
	Automatic Sprinkler [1970]	90.8 – 98.2
	Miller [1974]	86
	DOE [1982]	98.9
	Maybee [1988]	99.5[4]
	Kook [1990]	87.6
	Taylor [1990]	81.3
	Sprinkler Focus [1993]	98.4 – 95.8
	Linder	96
	Powers	98.8[5]
Residential	Milne [1959]	96.6
Institutional	Milne [1959]	96.6
Various	BRE [1973]	92.1
	Miller [1974]	95.8, 94.8
	Powers [1979]	96.2
	Richardson [1985]	96
	Finucane et al. [1987]	96.9 – 97.9
	Marryatt [1988]	99.5[6]

Table 3.19: Summary of Sprinkler System Effectiveness (Bukowski et al)

Budnick (2001) reviewed reliability data for sprinkler systems and concluded the mean value of reliability was approximately between 93% and 96%.

Rohr (2000) reported sprinkler system reliability (sprinkler operated as designed) for residential occupancies of 84.5%. This was across all residential occupancy types.

Studies by Ruegg and Fuller (1984) estimated sprinkler system effectiveness to be 92%.

Duncan and Wade (2000) assumed an effectiveness for sprinkler systems of 95%.

Enright (2003) assumed a probability of suppression (sprinklers effective in maintaining tenable conditions) of 99% and further assumed a normal distribution with one standard deviation being set as the difference between the mean and 100% resulting in a truncated distribution. The high probability was largely based upon the results of Marryat and the good life safety record of sprinklers in New Zealand.

Wade and Page assumed an asymmetrical PERT distribution for sprinkler system success, minimum value 90%, expected value 95% and maximum value 99%.

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[4] Strong inspection/maintenance regime (Power industry)

[5] Office buildings NYC

[6] Strong inspection/maintenance regime (Australia/NZ)

Houlding and Rew assumed a range of sprinkler system reliabilities with the focus being on effectiveness in a variety of chemical fire scenarios. The reliabilities ranged from 60% to 90% depending on the scenario.

Linder (1993) considered system reliability and for fully sprinklered buildings, the failure rate was around 3%.

US statistics [Rohr (2000)] indicate sprinkler system failure was due to deficient maintenance in over 50% of cases (of these around 70% was water supply being turned off). A further 14% of failures were due to over-stacking associated with warehouse type occupancies. In an updated report Rohr and Hall (2005) report that sprinklers failed to operate in 7% of structure fires and two thirds of these failures were due to water supplies being shut-off. Nearly all failures were reported as being due primarily to human error. The specific data for apartment buildings when adjusted for coding errors gave a 2% result for apartment fires where the sprinklers failed to operate. For 81% of apartment fires the system failed to operate due to the system being shut off. Manual intervention defeating the system accounted for the remaining 19% of failures.

Watanabe (1979) estimated approximately 2/3rd of failures were due to hardware issues and 1/3rd due to maintenance. This contrasts with the US experience.

Koffel (2006) believes the latest NFPA data indicates that reliability may be decreasing:

"... More recent data studies indicate that the operational reliability of sprinkler systems may be decreasing"

Based upon the NFPA data Koffel also believes some reliability estimates are overly optimistic.

"The NFPA data indicates that the commonly stated reliability of automatic sprinkler systems in the range of 96% (fails once in every 25 years) is overstating the reliability of sprinkler systems unless there are assurances that the preventative maintenance on the system is substantially better than that on the average system in a building in which a fire has occurred"

Koffel proposes a reliability for design purposes of 90%.

Number of Sprinkler Heads Operating

Rönty et al (2004) summarised the work undertaken by Baldwin and North and others. Statistical data on sprinkler system operation was analysed to yield probabilities for a certain number of sprinkler heads operating and the data fitted to expressions of the form:

$$f(n) = n^{-a} / \zeta(a) \text{ or } f(n) = n^{-(a-b\ln(n))} / c(a,b)$$

Where $f(n)$ is the probability of n sprinkler heads operating, $\zeta(a)$ is the Riemann zeta function, a, b and c are coefficients derived from the data. The table overleaf provides values for a number of studies. In most cases coefficients are provided for both equation forms, the exception being the New York high rise office which only has coefficients for the Riemann zeta function form.

Study	**Sample Size**	a	b	$\zeta(a)$	$c(a,b)$
NFPA wet	66000	1.7	-	2.05	-
		1.5	0.05	-	2.19
IRI	1470	1.5	-	2.57	-
		1.2	0.12	-	2.49
FM	2860	1.4	-	2.99	-
		0.6	0.25	-	3.52
New York High Rise	84	2.5	-	1.34	-
Japan (2 Studies)	204	2.6	-	1.31	-
	96	1.0	0.01	-	7.00

Table 3.20: Correlation Parameters for Number of Sprinkler Heads Operating

Thomas (2002) compared the relative effectiveness of sprinklers, alarms and protected construction across a range of occupancy types. Based on NFIRS data he concluded that in general sprinklers alone were more effective than a combination of alarms and protected construction. Effectiveness was measured as a percentage change in outcome compared with a base case of no systems being present.

Smoke Management

Zhao (1998) estimated smoke control system reliability using fault tree analysis. He concluded that zoned smoke control systems have a reliability of between 52% and 62% for buildings greater than 5 storeys high and less than 20 storeys high. The derived reliability for stair pressurisation systems was 90%. Zhao also discussed the effect of maintenance regimes and damper system design on system reliability.

Taylor (1975) commented on effectiveness of well designed pressurisation systems. Taylor expressed doubts about the effectiveness of sprinkler systems in the pressurised area (corridor).

Klote and Milke (2002) reviewed the reliability of five smoke management systems of increasing complexity. The reliability of the system declined rapidly based upon the assumption that there was no redundancy in the system design (i.e. any single failure would be critical). Reproduced in Table 3.18 below.

Case	**# of HVAC fans**	**# of other components**	**Reliability pre-commissioning**	**Mean life of commissioned system (months)**
1	3	0	0.97	116
2	0	3	0.83	46
3	3	9	0.56	14
4	5	18	0.31	8
5	5	54	0.03	3

Table 3.21: Smoke System Reliability (Klote and Molke)

Harrison and Spearpoint (2006) discussed smoke management system reliability, expressing concern over the efficacy of these systems.

"Smoke management systems can be complex and involve the operation of many interacting components, including detection systems, exhaust fans, natural ventilators, automatic smoke curtains, dampers, fresh air intakes, etc. Experience of actual installed systems in real buildings has led to concerns on the efficacy of some smoke management systems, especially over the lifetime of a building."

The authors reported the work of Moran who surveyed a number of smoke management systems in Australia and found that 1/3rd of the systems surveyed had reliability problems the majority related to fans.

Fazio (2004) researched the effectiveness of stair pressurisation systems. She commented on the importance of system commissioning,

"... the commissioning stage of SPS is one of the most critical aspects in obtaining an effective system. Commissioning of the SPS may take many years before it is made operational as designed, thereby resulting in the building possibly not being protected as designed ..."

Fazio also reported on a number of full scale fire tests.

"From these early tests, the level of pressurisation required was found to be dependent on whether or not the building was sprinkler protected. For example; DeCiccio's (1973) full-scale fire experiments showed that "smoke-free" exits could be obtained for an unsprinklered large fire (Klote and Milke) where pressurisation was provided. Another finding was that the minimum design pressure differentials for a non-sprinkler protected building are almost double those required for a sprinkler protected building, i.e.; 12Pa for a sprinklered building and 20Pa for a non-sprinklered building (NFPA 1993)"

Fazio (2007) published research into the effectiveness of stair pressurisation systems. In this work the earlier fault tree analysis was developed further to estimate the effectiveness of systems. Surveys of the industry were undertaken to provide estimates for failure rates of specific fault tree components. Fazio also carried out a sensitivity analysis looking at the effect of environmental factors (wind, temperature, leakage from building) on system performance; this was undertaken using the CONTAM model. Two system configurations were assessed, one which had a variable speed drive (system 1) and one with a damper (system2). The environmental factors and system factors were considered independently. The primary conclusions were that system factors were more important than environmental factors in determining system performance, that quality of installation, commissioning and maintenance had a significant impact on system effectiveness, and effectiveness (in terms of AS 1668.1 compliance) was gauged as being relatively low at 52% for a system with a variable speed drive (VSD) and 84% for one utilising a relief damper. These values were optimistic in that they assumed perfect performance of the Fire Indicator Panel (FIP) microprocessor output signal for system 1, and perfect damper performance for system 2. Without this adjustment the effectiveness rates were of the order of 49% for system 1 and 30% for system 2.

The work of Moore and Timms (1997) was described. For the two simple systems they analysed, the reliability was highly dependent on the quality of installation, commissioning and maintenance. For a system efficacy of >75% the probability of attainment was 64% or 79% for a low quality of work, 94.9% or 96.8% for a moderate quality of work, and 97.4% or 97.9% for a high quality of work. Moore and Timms also produced a general commentary on the effect of the quality of work presented in Table 3.22.

Installation or Commissioning Quality	Probability of installation fault	Probability of failure to detect a fault
High	0.01	0.003
Medium	0.16	0.01
Low	0.3	0.1

3.22: Impact of Quality on Reliability (Moore and Timms)

The values in Table 3.22 are consistent with those referenced by Zhao from Lees.

System Effectiveness Based on Fatality and Injury Data

Brennan (1999) reports most fatalities in residential fires occur in the compartment of fire origin. Hall (1994) reports that 50% of victims are located close to fire. Meacham (1999) reports a US study from the 1970's which reported 70% of adult victims were intoxicated. Other studies have shown a smaller but still significant proportion of victims who were intoxicated including the 12.5% males and 4.8% females reported by Conley and Fahy (1994).

For apartment buildings Hall (1994) reported that smoke detectors represented a 14% improvement in life safety over the case of no smoke detectors.

Building Research Establishment (BRE) research by Williams et al. (2005) indicates that the effectiveness (in terms of % reduction in loss of life) of sprinklers increases as fire area increases. Their estimate was that the reduction in loss of life due to sprinklers was significant for fires greater than 1m^2 to 2m^2 in fire area, which from their UK statistics gave a reduction between 55% and 85%. This is consistent with the 73% reduction reported by Rohr (2002) based on US statistics. The corresponding reduction in injuries from the UK data was between 15% and 45%.

Ramachandran (1993) found that the evidence suggested sprinklers had little influence on outcomes for fires <3m^2 in area. However this was based on commercial/industrial fires and with the lower ceiling heights and faster response associated with high rise buildings the 1m^2 to 2m^2 range suggested by Williams et al seems appropriate. The work by Wade and Duncan (2000) estimated a reduction of 80% in loss of life for a compliant sprinkler system, 53% for smoke alarms alone, and 83% for a combination of smoke alarms and sprinklers. Ruegg and Fuller (1984) estimated the following reductions in death rates:

Case	Reduction in loss of life
Installing sprinklers	69%
Installing smoke alarms	53%
Sprinklers plus smoke alarms	82%
Marginal benefit for installing sprinklers when smoke alarms already present	63%

Table 3.23: Reduction in Loss of Life (Ruegg and Fuller)

Studies on Scottsdale by Ford (1997) indicate a 98.5% reduction in loss of life but this is based on a small sample size and hence uncertainties are high.

Summary table (Table 3.24) of reduction in death and injury for various studies from Williams et al (2004)

Source	Reduction in deaths			Reduction in Injuries		
	Alarm Only	Sprinkler Only	Sprinkler + Alarm	Alarm Only	Sprinkler Only	Sprinkler + Alarm
BRANZ	53%	80%	83%	70%	63%	75%
US Apartment data		81%				
NIST estimate	53%	69%	82%		46%	
NFPA estimate		73%				
Scottsdale	50%		98.5%			
Vancouver		47%[7]				

Table 3.24: Summary Data of Reduction in Death and Injury Rates (Williams et al.)

Thomas (2008) presented Australian data for residential fires as well as analysis of US statistics and commented that the reduction in death and injury rates based on statistical estimates is *"…far lower than is assumed"*.

Rohr and Hall estimate a 91% reduction in loss of life due to sprinklers in hotel and motel occupancies compared with 74% for residential occupancies. US statistics indicate around 35% of high rise apartment structure fires occur in sprinkler protected buildings. The proportion is believed to be growing as the building stock changes. Generally sprinklers are installed in the properties which would have occupants of a higher socioeconomic standing and therefore a lower inherent fire risk. Therefore it could be expected the percentage figures underestimate the percentage of high risk protected apartment units in the overall building stock.

For apartments Rohr and Hall estimate that in 51% of cases the fire was too small to operate the sprinkler system. The overall figure across all residential occupancies was 58%.

The extent of flame damage for apartment and office properties is contrasted in Table 3.25 below:

Extent of Flame Damage	Apartments		Offices	
	With Sprinklers	Without Sprinklers	With Sprinklers	Without Sprinklers
Confined to object of origin	69%	46%	68%	47%
Confined to area of origin	20%	25%	21%	23%
Confined to room of origin	6%	11%	6%	8%
Confined to fire-cell of origin	2%	2%	1%	1%
Confined to floor of origin	1%	4%	1%	4%
Confined to structure of origin	2%	10%	2%	15%
Extended beyond structure of origin	0%	2%	0%	2%

Table 3.25: Extent of Fire Spread (Rohr and Hall)

Rohr and Hall estimate sprinklers account for 1% of controlled fires reported to the fire brigade in apartments and 3.1% in offices. In practice these percentages will be lower because of unreported fires.

Ahrens (2007) reports that during 2000 - 2004 there was one reported civilian death and fifteen injuries in office property with smoke detection systems installed, based on a total number of fires of 880. For the case of the fatality it was not able to be determined if the system was operating correctly at the time of the fire. Death rates for apartments were 390 deaths from 94,700 fires. It is

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[7] Highly pessimistic figure as based upon assumption all properties sprinklered.

not possible from Ahrens work to determine the proportion of these which were domestic type alarms systems and which were commercial systems.

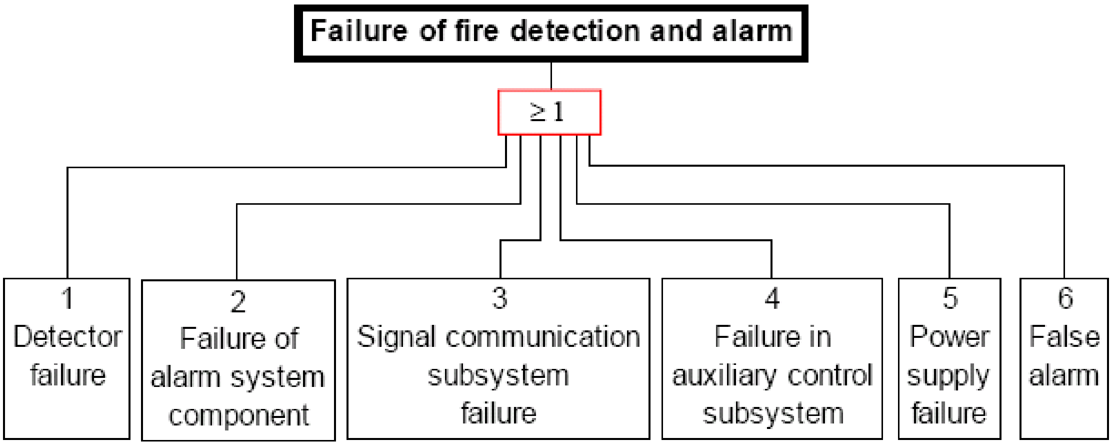
For apartment fires the percentage of fatalities relative to fire events was 1% to 2%. There was no specific data given for commercial smoke detection systems compared with domestic alarms (battery and hardwired) but it would be reasonable to expect that the life safety effectiveness of commercial systems would be at the lower end of this range.

Modelling of System Failure

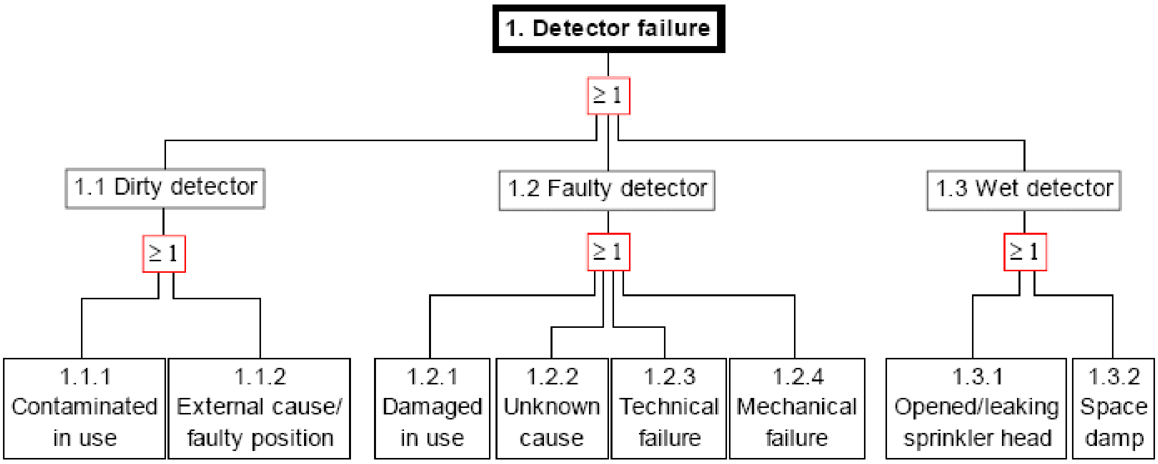
A number of authors have modelled the failure of fire protection systems using fault tree methods.

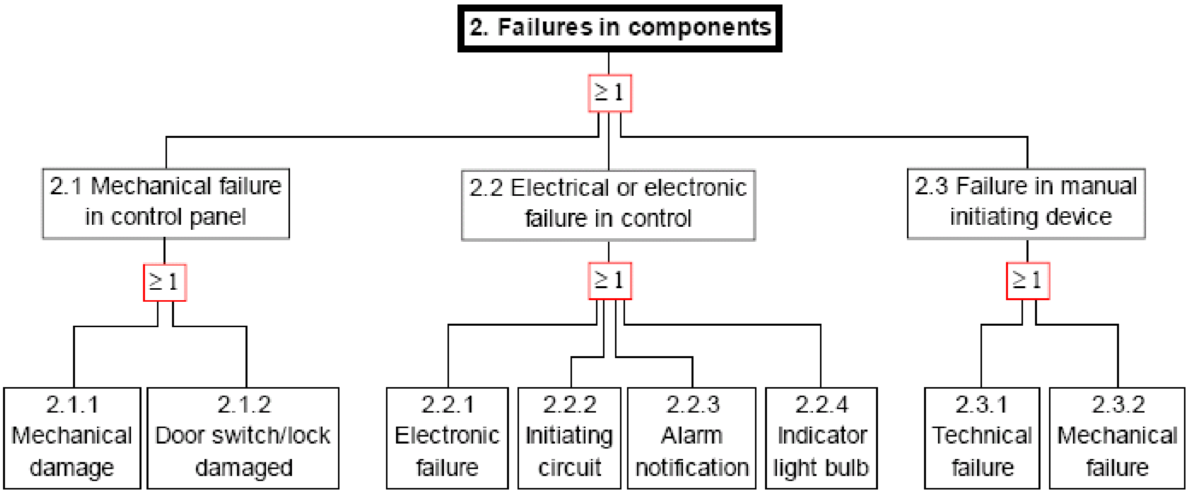
Alarm Systems

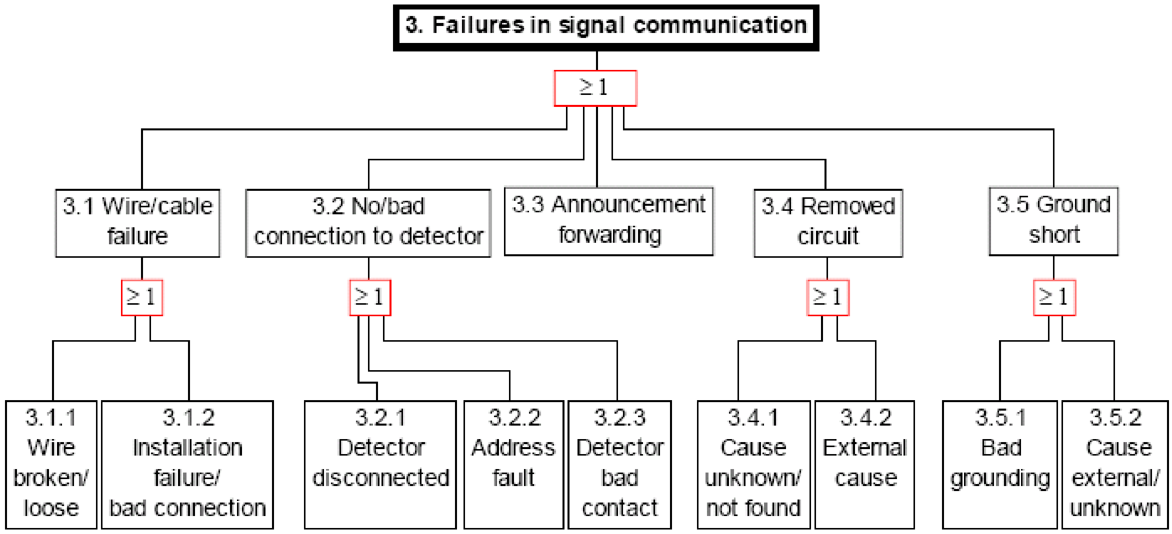
Nyyssönen et al modelled alarm system failures using the following fault tree structure.

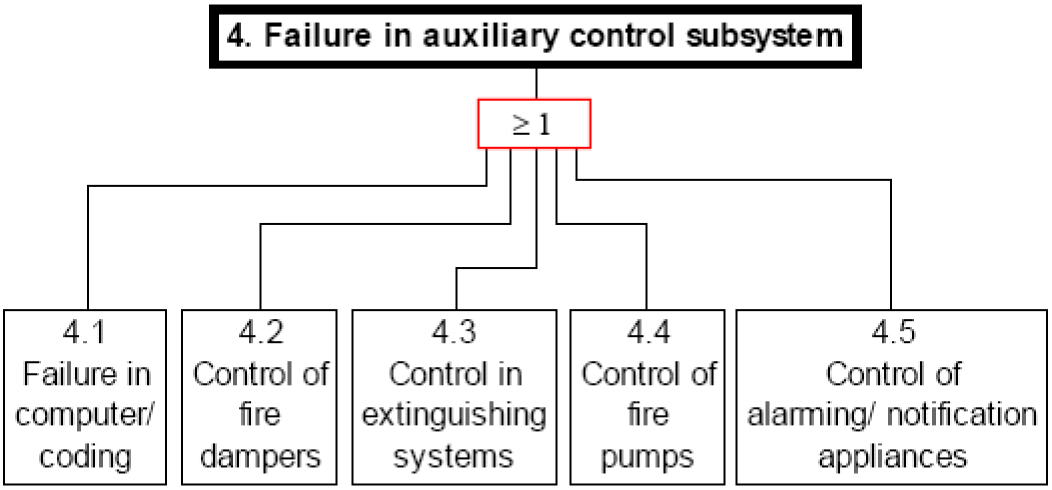


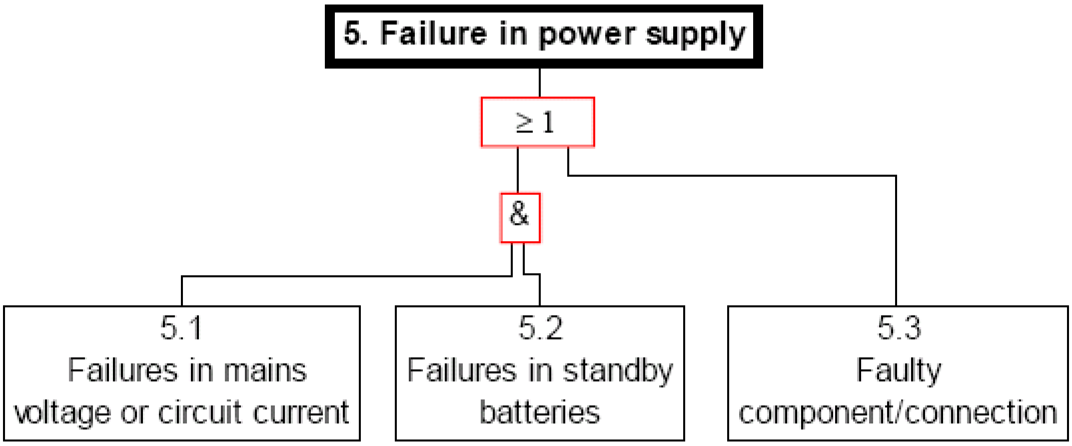
Each of these being further detailed with the following subsidiary trees:

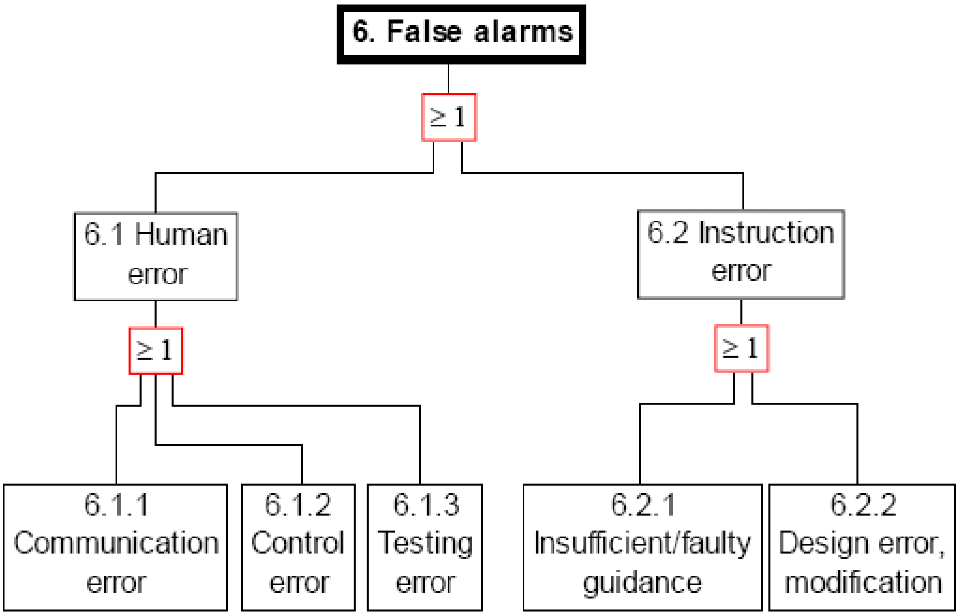



2. Failures in components
≥ 1
2.1 Mechanical failure in control panel
2.2 Electrical or electronic failure in control
2.3 Failure in manual initiating device
≥ 1
≥ 1
≥ 1
2.1.1 Mechanical damage
2.1.2 Door switch/lock damaged
2.2.1 Electronic failure
2.2.2 Initiating circuit
2.2.3 Alarm notification
2.2.4 Indicator light bulb
2.3.1 Technical failure
2.3.2 Mechanical failure


3. Failures in signal communication
≥ 1
3.1 Wire/cable failure
3.2 No/bad connection to detector
3.3 Announcement forwarding
3.4 Removed circuit
3.5 Ground short
≥ 1
≥ 1
≥ 1
≥ 1
3.1.1 Wire broken/ loose
3.1.2 Installation failure/ bad connection
3.2.1 Detector disconnected
3.2.2 Address fault
3.2.3 Detector bad contact
3.4.1 Cause unknown/ not found
3.4.2 External cause
3.5.1 Bad grounding
3.5.2 Cause external/ unknown

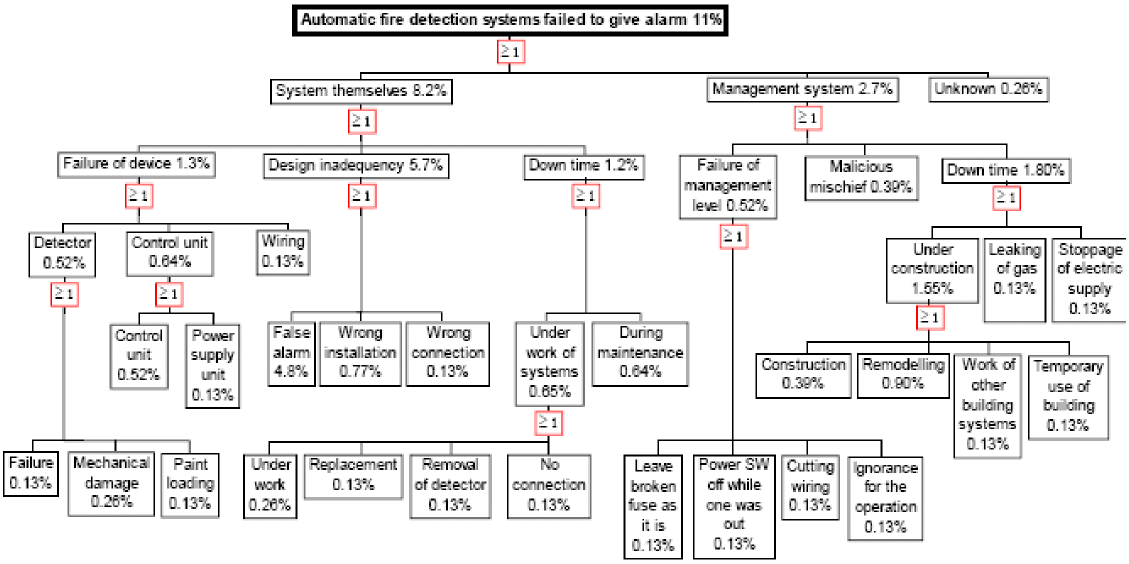

4. Failure in auxiliary control subsystem
≥ 1
4.1 Failure in computer/ coding
4.2 Control of fire dampers
4.3 Control in extinguishing systems
4.4 Control of fire pumps
4.5 Control of alarming/ notification appliances


5. Failure in power supply
≥ 1
&
5.1 Failures in mains voltage or circuit current
5.2 Failures in standby batteries
5.3 Faulty component/connection


6. False alarms
≥ 1
6.1 Human error
6.2 Instruction error
≥ 1
≥ 1
6.1.1 Communication error
6.1.2 Control error
6.1.3 Testing error
6.2.1 Insufficient/faulty guidance
6.2.2 Design error, modification

Sprinkler Systems

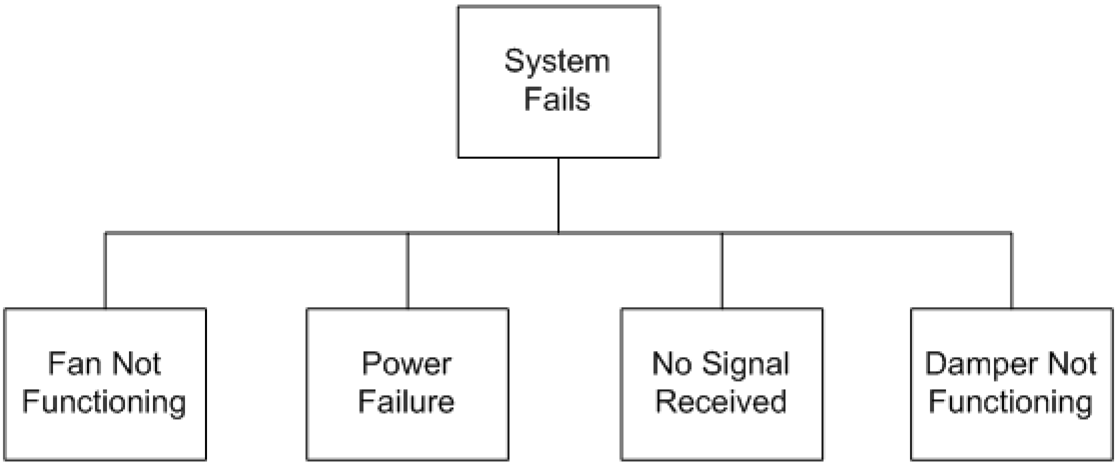
Watanabe (1979) derived the following fault tree based upon studies of maintenance records of 777 Japanese sprinkler systems.



Various alternative trees presented for sprinkler system reliability.

Smoke Management

Zhao has developed a fault tree model for assessing reliability of smoke detection system. The top level of the fault tree used by Zhao is presented below.



Fazio (2007) expanded on previous work of 2004 and produced this more comprehensive and detailed fault tree (below).

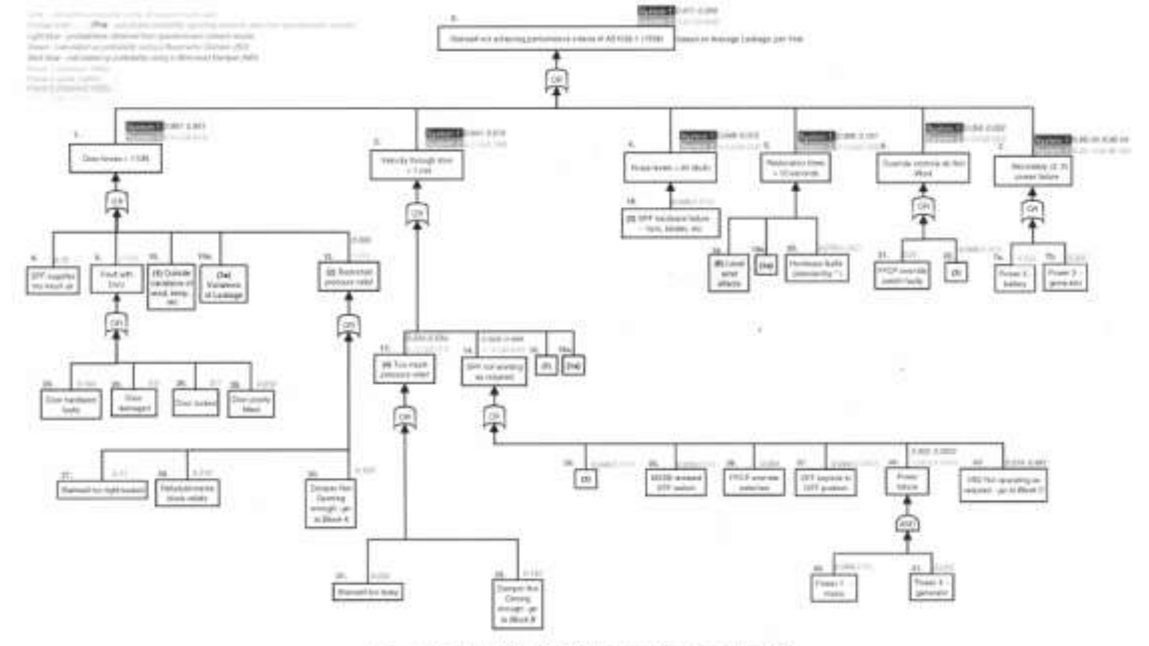


Figure 47. Modified Fault tree for Systems 1 and 2

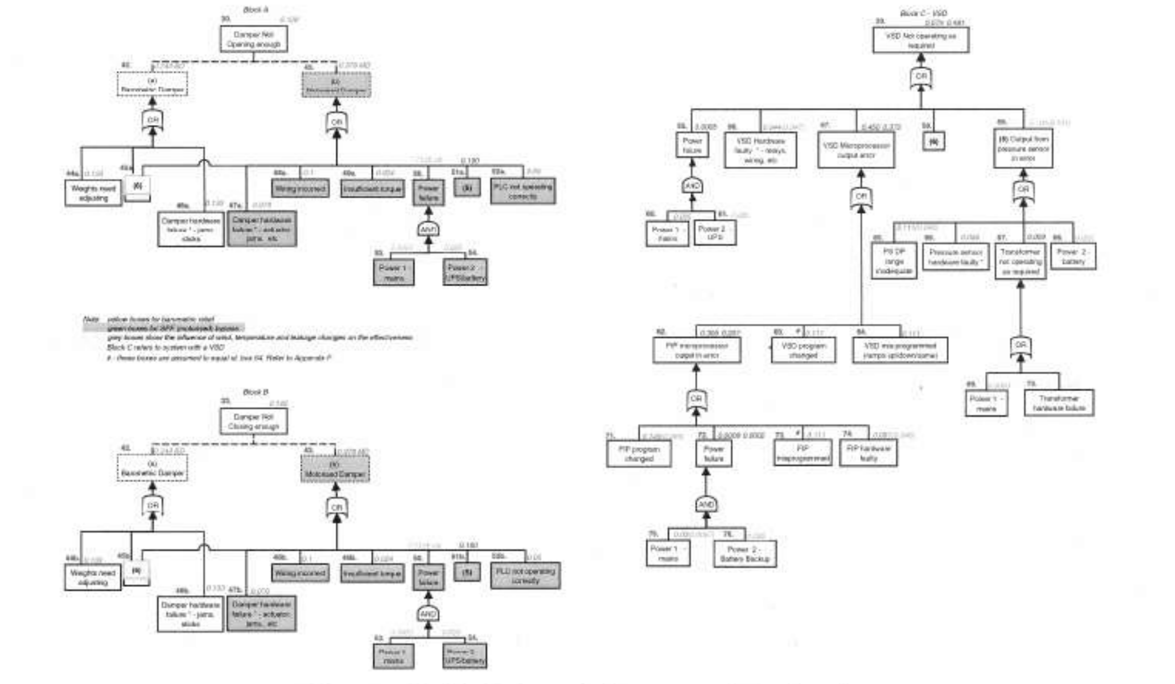


Figure 47. Modified Fault tree for Systems 1 and 2 (continued)

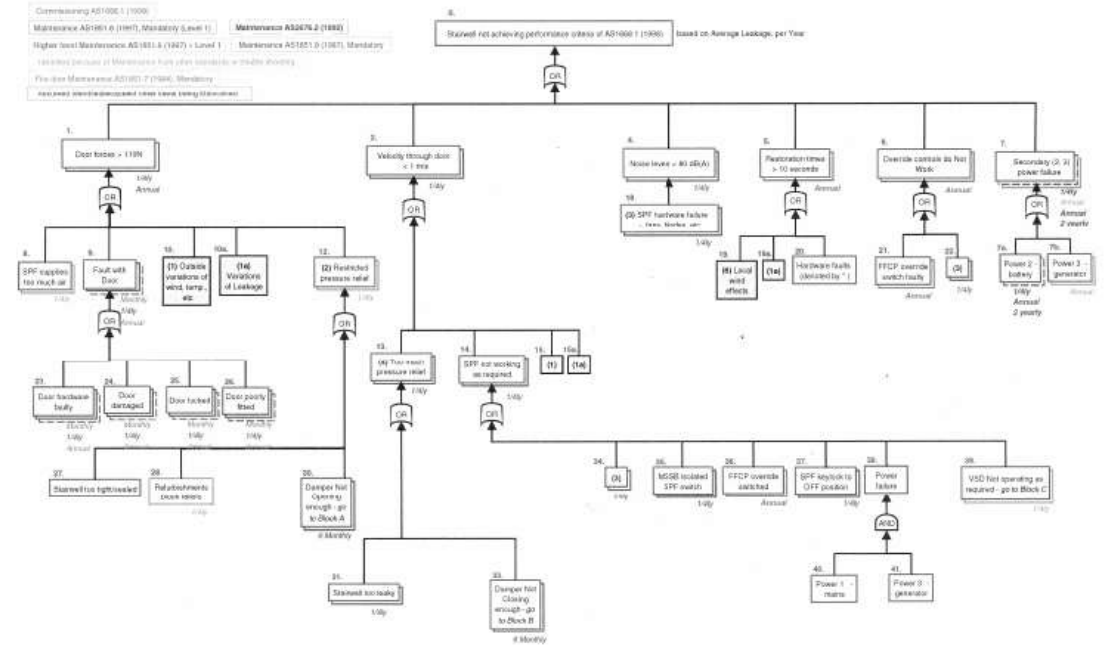


Figure 48. Commissioning and Maintenance routines associated with identified Faults

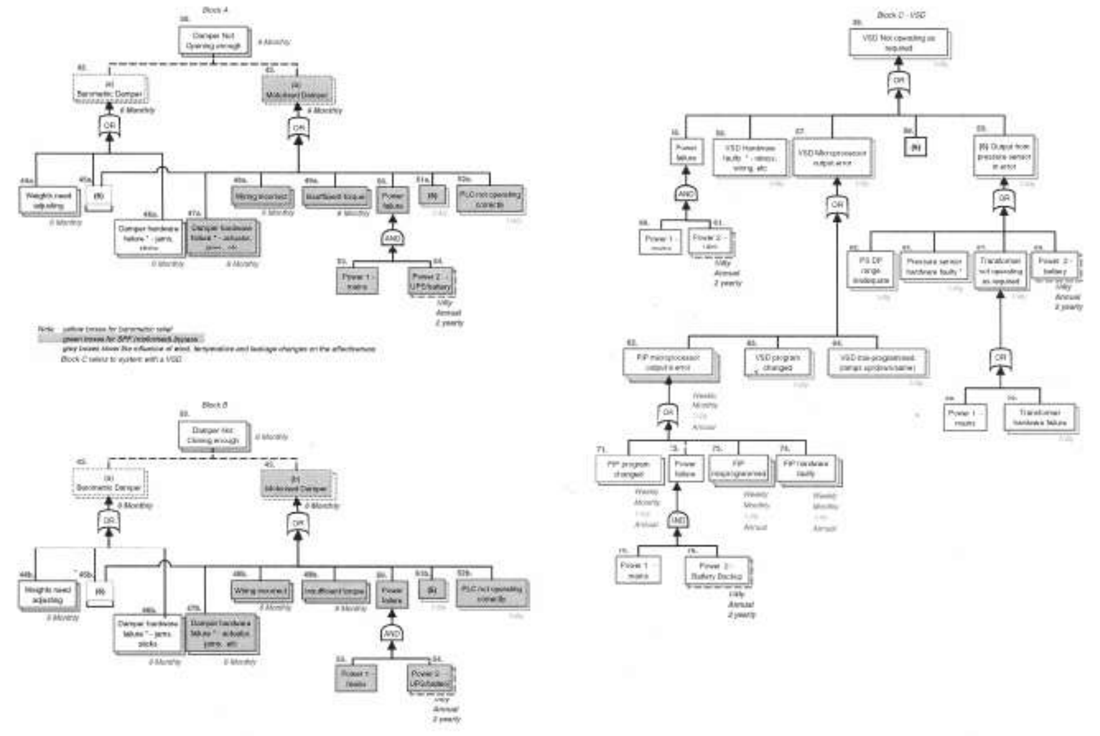


Figure 48. Commissioning and Maintenance routines associated with identified Faults (continued)

Quantitative Risk Assessment

The literature on QRA and its application to fire is of interest to give some historical context.

Bukowski et al. (1990) developed a methodology for quantifying fire risk in order to compare the risk level for different building types. Charters (1996) used QRA methods (event trees) for assessing life safety risk in a hospital. QRA methods for fire have subsequently been adopted in a number of design documents, for example the International Fire Engineering Guidelines (2005), and text books including Barry (2002).

4

Role of Fire Risk Software

A number of software packages exist for assessing fire risk. A number of these are scenario based models which include FiRECAM (Yung 1997), CRISP II (Fraser-Mitchell 1994), FIRE-RISK (CESARE Risk) (Beck 1998), FIERAsystem (Benichou et al. 2002), PFS (Hostikka et al 2002, 2003). Other risk ranking tools exist but these are not suitable for risk assessment for performance based design as they are qualitative in nature.

FiRECAM (Fire Risk Evaluation and Cost Assessment Model) provides a model for assessing fire risk it is scenario driven and assesses the likelihood and consequences of fire. It uses default deterministic reliability/effectiveness measures for systems which can be changed buy the user. Default values are 90% for sprinkler system reliability and suppression effectiveness, 80% for detector effectiveness and central panel effectiveness.

CRISP is a Monte Carlo zone model – it calculates egress and fire conditions and carries out a probabilistic tenability analysis to derive the risk measure.

PBS is another Monte Carlo zone model – using CFAST as the underlying zone model.

FIRE-RISK is another model which incorporate fire growth and spread, mitigation measures and occupant response.

FIERAsystem this is based upon FiRECAM and has application for light industrial type occupancies.

Other software is being developed. RMS (Reliability Management Software) for example are developing portfolio risk models (aggregated across multiple risks) and individual site/building models. The approach of the former uses failure surfaces built up from loss databases, the latter uses a module approach to calculate response of building to fire scenarios. The reliability is built into this model and is handled in a similar way to other models such as FiRECAM.

BRANZ is also researching (together with the University of Canterbury) the use of a probabilistic engine in combination with the BRANZFIRE zone model. This would in principle allow the use of reliability (effectiveness) distributions if this parameter were included in the probabilistic engine.

In conclusion there is no specific software known to the author for predicting fire protection system reliability. The risk models discussed use reliability values to predict various outcomes from scenarios, and the use of distributions is limited.

5

New Zealand Statistics and Data Sources

Fire Service Statistics

New Zealand fire service data is collected via the Fire Incident Reporting System (FIRS). The information for fire system performance available for multi-storey office and apartment developments is limited. Firstly genuine fire calls to these occupancies are not common (structure fires accounting for ~ 6000 pa, apartments for <200 (not all of which are necessarily structure fires, offices typically for <160 and not all of these are high rise and not all structure fires). A number of these may be associated with spaces which do not directly relate to tenability for high rise office and apartment buildings for example garage spaces, roof level plant rooms, etc. Additionally a significant proportion of these are reported as having no associated damage but it is unclear whether this can be assumed to mean that conditions never threatened to become untenable.

Reporting of fire system performance is imperfect (Challands, 2007) data collection is incomplete and the scope of information collected restricted. From the emergency incident statistics report sprinklers account for around 7% of system activations (approximately 100 cases per year) and monitored smoke detector systems for around 30% of system activations.

Where the detector is in the room or space of fire origin it is reported as not operating in 17% of cases and the fire being too small to operate the detector in a further 10% of cases.

Where the system is reported as having operated it is recorded as being ineffective in less than 1% of cases.

The reported reasons for detector failure are summarised in tables 5.1 and 5.2 below. Table 5.2 shows the data excluding cases where discharge heads/detectors were reported as not being in the room or space of fire origin and cases where reason for failure is unknown. Table Data is accumulated data for 2001 to 2006. Tables give the mean and the standard deviation from year to year.

Total number of cases for this subset of data in Table 5.2 varied between 47 and 122 depending on the year. The total number of cases for the complete data set varied between 74 and 242. The lower number of cases were associated with the earlier years and values are relatively constant (within 10%) for the last 3 years.

Reported Reasons for Failure	# Cases	Average	S.D.
Power Supply Failed	9 – 27	21.0%	3.9%
Improper installation/placement of detector	8 – 30	19.5%	7.9%
Defective Detector	7 – 14	12.4%	5.5%
Inadequate maintenance	17 – 47	37.1%	6.5%
Water in System	0 – 1	0.5%	0.7%
System shutdown	1 – 7	4.6%	2.1%
Not enough agent discharged to control fire	3 – 5	3.6%	2.5%
Extinguishing agent discharged but did not reach fire	1 – 3	2.0%	1.0%
Extinguishing system piping damaged or blocked	0 – 1	0.2%	0.5%

Table 5.1: Reported Reasons for Failure excluding no detector/heads in the room and unknown (FIRS, 2001 - 2006)

Reported Reasons for Failure	# Cases	Average	S.D.
Power Supply Failed	9 – 27	10.8%	2.2%
Improper installation/placement of detector	8 – 30	10.4%	5.7%
Defective Detector	7 – 14	6.8%	3.9%
Inadequate maintenance	17 – 47	18.9%	3.2%
Water in System	0 – 1	0.2%	0.4%
System shutdown	1 – 7	2.2%	0.6%
Not enough agent discharged to control fire	3 – 5	2.0%	1.5%
Extinguishing agent discharged but did not reach fire	1 – 3	1.0%	0.5%
Extinguishing system piping damaged or blocked	0 – 1	0.1%	0.2%
No discharge heads/detectors in room or space of fire origin.	0 – 1	8.6%	4.5%
Unknown	0 – 1	26.6%	4.6%
Extinguishing system piping damaged or blocked	0 – 1	13.0%	17.5%

Table 5.2: Reported Reasons for Failure (FIRS, 2001 -2006)

The FIRS database was queried to identify fire events for multi-storey office and apartment buildings which met any of the following criteria:

1. (Detector) in the room of origin but did not operate.
2. (Detector) in the room of origin but fire too small to activate.
3. (Detector) not in room of origin and did not operate.
4. System operated but was ineffective.

The definitions and applicability of each of these is open to some degree of interpretation by the officer reporting the fire.

The breakdown of the raw data for the period 2001 to 2006 against these headings is summarised in Table 5.3 below:

Detector in room of origin	
- Did not operate	33
- Fire too small	22
Detector not in room of origin	
- Did not operate	27
- Operated but ineffective	2
Total	**84**

Table 5.3: Detector performance in multi-storey office and apartment fires

Filtered for repeats, miscoding and domestic type systems the numbers for specific subsets are as follows:

Detector in room of origin	**Office**	**Apartment**	**Total**
- Did not operate	13	2	15
- Sprinkler	1[8]	0	1
- Monitored smoke detection	8	2	10
- Heat detection	4	0	4
- Fire too small	22	4	26
- Sprinkler	5	3	8
- Monitored smoke detection	5	1	6
- Heat detection	12	0	12
Detector not in room of origin			
– Did not operate	18	6	24
- Sprinkler[9]	1	1	2
- Monitored smoke detection	12	5	17
- Heat detection	5	1	6
Operated but ineffective	0	1	1
Total	53	13	66

Table 5.4: Detector performance details in multi-storey office and apartment fires

The key observations are as follows:

- There was only one clear case of sprinkler system failure and that was where a floor was isolated. It was not reported whether the valve was monitored or not. The smoke detection system operated. Brigade report salvage operations so the fire was large enough to cause some damage but it is unclear whether there would have been a major loss without brigade intervention.
- There was no recorded incident of stairwell pressurisation system failure.
- There was evidence that a significant number of cases were coded as did not operate whereas the appropriate coding was “fire too small”. This was particularly true for sprinklers and heat detectors for the simple reason that these devices require significant fires to operate.
- Location of origin of fires is tabulated below.
  - Kitchens were well represented and represent a higher proportion of living area fires in the general statistics. It is proposed this may be because of tampering with smoke detectors in an

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[8] Another case A592709 was recorded as failure to operate, fire was in apartment living area with no damage recorded. Suspect this was a fire that should have been coded as fire too small to operate detector. Needs further investigation.

[9] In each of these cases it was not clear what occurred from the details given in the FIRS report. No damage was recorded and fires started in occupied areas. It is likely that neither of these cases represent a failure of the sprinkler system. Needs further investigation.

attempt to minimise nuisance alarms. By comparison incidence of failure associated with bedroom fires was low though the sample size is small.

Location of Origin	Location of Origin	Count	%
Living spaces	Bedroom	1	1
	Kitchen	11	11
	Lounge	3	3
	subtotal	*15*	*15*
Means of egress	Hallway, passage	9	9
	Stairs	1	1
	subtotal	*9*	*9*
Office type spaces	Manufacturing, work room	4	4
	Office	3	3
	Showroom	3	3
	Meeting Room	1	1
	subtotal	*11*	*11*
Toilet	Toilet	3	3
Concealed spaces, IA spaces	Roof space	8	8
	Wall space	1	1
	Machinery Room	8	8
	subtotal	*17*	*17*
External	External	1	1
	total	***56***	

Table 5.5: Location of Fires where Failure Occurred

- Hallway or passage fires were well represented. These were recorded for office occupancies. Fire sizes appear to be small with no recorded damage for any of the cases and 3 of the cases being explicitly identified as fires where the fire was too small to activate the detector.
- Toilet fires are a significant proportion of deliberately lit fires in office spaces.
- Concealed spaces fires and plant room type fires represented a significant number. It is proposed that some failures represented here were not failures of the detectors themselves but cases where either the fire was too small or located in a position where the detector could not be reasonably be expected to operate.
- The external fire was a rubbish bin fire where the detector did not activate. It is possible that this may have been due to poor placement, small fire size but there is insufficient information to determine this with any confidence.

Statistics were also obtained from the New Zealand Fire Service on the proportion of fires that were recorded with a termination stage of smoulder (i.e. the fires never progressed beyond smouldering fires).

General Property Use Group Name	Smoulder only	Incident ID	Percent
Construction, Renovation	4	37	11%
Residential - Sleeping	1,284	3198	40%
Residential -Outbuilding	48	357	13%
Commercial, Retail, Manufacturing, Storage	387	1003	39%
Educational	85	207	41%
Health, Institutional	118	196	60%
Recreational, Assembly	65	204	32%
Communications, Research	7	17	41%
Rural, Farming, Forests	51	167	31%
Utilities, Disposal	7	23	30%
Transportation	18	41	44%
Water Areas	3	4	75%
Other	8	28	29%
Not Recorded	0	4	0%
Total	2,085	5,486	38%

Table 5.6: Number of Fires with Smoulder Termination Stage

The proportion recorded is significantly higher than other sources such as Ahrens. It is possible this represents a number of fire scenarios which would not be considered as smouldering fires for the purposes of life safety evaluation. It does for example explicitly include overheating. It would also be expected to include a significant number of very small fire events and also events which were flaming but then became smouldering with consumption of fuel. There is also likely to be a proportion of miscoded events.

Insurance Industry Statistics

Insurance industry statistics that can be used to determine system reliability are not available for New Zealand (McRae). In general insurers do not have analysable statistics on fire protection systems installed in their portfolio of risks. Data from losses and failure events is not collated and would require analysis of individual incident reports to determine if a fire protection system was installed. Even then there is no protocol for recording information on fire protection system performance.

Oldnall (2007) confirms responses from McRae. The re-insurance industry has no reliability dataset for New Zealand. Rating models exist but these are not explicitly tied to system reliability. The rates are based upon historical loss ratio data and will vary according to Market conditions so do not even offer an indirect measure of reliability.

O’Brien (2007) reported that Factory Mutual in Australia is understood to have collected information on sprinkler system water supply reliability, however this information is not in the public domain.

The Insurance Council of New Zealand (ICoNZ) holds some member data on claims (Lucas) but the purpose of this database is to identify fraud and it does not hold data suitable for determining system reliability. Discussion with the commercial committee of ICoNZ confirmed that some member companies hold data on large losses but these are not in a form where they could be readily analysed to identify system failure.

Actuarial Data

Actuarial services in New Zealand and Australia do not have reliability data on specific fire protection systems. Information for underwriting purposes is based upon general loss histories across industry sectors, construction types and water supplies. This information allows prediction of the losses expected but does not contain explicit measure of reliability and effectiveness as this information is masked by the broad base of data.

Actuarial analysis can be undertaken to analyse losses for an individual business or group of businesses and is used in this way to assess the ability of businesses to meet their risk financing requirements. The fire data available is generally limited and statistical techniques are used to allow these limited datasets to be used to predict anticipated future losses. In principle it is possible to augment this approach with analysis of system reliability and effectiveness together with fire incidence data to establish the form of the loss profile for a particular case. This is not generally done in practice.

New Zealand Fire Protection Industry Surveys

Surveys have been undertaken with representatives from the fire protection industry including designers, installers, maintainers and surveyors of systems.

Samples of the survey forms have been included in Appendix A. The survey results have been incorporated into the reliability estimates developed in Section 10.

Summary survey results for sprinkler system faults are presented in table 5.7. These values are based upon surveys of the New Zealand fire protection industry including contractors such as Wormalds and Chubbs as well as the companies carrying out surveys of sprinkler systems (Fire Protection Inspection Services, Central Inspection Services).

Fault Condition	**Mean**	**Standard Deviation**		
Water Supply Isolated	0.0017	0.0028	0.0010	0.0013
Water Supply Impaired	0.0050	0.0063	0.0050	0.0063
Water Supply Inadequate	0.031	0.026	0.024	0.015
Diesel Pump failure	0.0030	0.0054	0.0016	0.0020
Electric Pump failure	0.0038	0.0034	0.0027	0.0023
No monitoring of isolation valves	0.024	0.032	0.017	0.021
No monitoring of floor isolation valves	0.051	0.058	0.019	0.017
Unprotected ceiling spaces	0.0056	0.0073	0.0055	0.0073
Unprotected rooms	0.060	0.059	0.014	0.015
Alarm signalling not operational	0.0086	0.011	0.0086	0.011
Alarm sounders not working	0.0054	0.011	0.0054	0.011
Sprinklers with cracked bulb	0.053	0.045	0.030	0.035
Isolation of whole system/multiple systems	0.02	NA	0.02	NA
Panel Hardware faults	0.001	NA	0.001	NA

Table 5.7: Summary Survey Results for Sprinkler System Reliability

The survey results in table 5.8 are highly dependent on the work of Fazio. Some additional data from NZ sources has been included (from the main contractor for these systems, Climatech as well as the main organisation acting as an IQP and commissioning engineer for these systems in New Zealand). The survey forms used to record the data were based upon those of Fazio.

Fault	**Mean**	**St Dev**
Wiring/Cabling		
Wiring fault1 associated with..		
FIP (fire indicator panel)	9.33	19.23
SPF (stair pressurisation fan)	11.00	21.84
MSSB (mechanical services switchboard for SPFs)	10.60	24.56
VSD (variable speed drive)	4.75	5.34
Smoke/other detector	2.33	2.25
Relay fault1 associated with..		
FIP (fire indicator panel)	5.50	9.08
SPF (stair pressurisation fan)	7.00	11.90
MSSB (mechanical services switchboard for SPFs)	15.80	27.12
VSD (variable speed drive)	2.75	4.86
Fault with pressure sensor		
Incorrect pressure sensor installed (eg out of range, low pressure sensitivity)	9.55	15.82
Blocked tubing	3.30	3.83
Electrical malfunction	5.00	3.61
Supply voltage applied to output	1.20	1.79
Pressure reading not stable, non repetitive(*)	6.44	7.13
Calibration shift due to overpressure	4.17	4.92
Differential pressure location not established/incorrect	13.82	14.91
Other? (please state)	10.00	NA
Fault with damper		
Damper does not close (more) when required	12.50	7.56
Damper does not open (more) when required	11.00	7.07
Damper jammed/sticking	15.25	6.93
Damper not operational because of actuator fault1	8.60	6.70
Damper does not open because installed motor has insufficient torque	1.71	2.29
Damper weights need adjusting	12.50	7.07
SPFs		
SPF does not work because..		
Broken fan blades	0.75	1.75
MSSB has isolated the SPF to be off, so fan doesn't run	2.60	3.95
FFCP (fire fan control panel) has overridden the SPF to off/stop, so fan doesn't run	0.43	0.53
Keylock switch (ie isolator switch) at SPF is off, so fan doesn't run	3.78	9.87
Power failure to SPF (note type of power)	5.11	13.11
SPS with VSDs and the BSD is fault1 (eg not sending correct signal to SPF, so fan speed's not correct)	10.09	15.24
Slipped fan belts	0.33	0.82
SPFs shaft/keyway sheared	0.14	0.38
SPFs discharge damper/bypass damper closed (when should be open)	4.20	5.39
FIPs		
FIP does not work because…		
Microprocessor inside FIP does not work	4.33	5.17
FIPs program has changed since commissioning	11.90	15.34
No power to FIP	2.00	3.95
Damper Motors/Actuators		
Damper/Actuator does not work because…		
Motor runs backwards	9.08	14.84

Fuses incorrectly installed	1.29	1.80
Incorrect fuses	1.50	1.69
Actuator mechanism has not been correctly adjusted	11.67	12.79
Fault with VSD		
Algorithm mis-programmed/altered in VSD	7.89	9.62
Power failure to VSD (note type of power)	1.44	2.13
Microprocessor fault1 with VSD	2.00	1.84
Relays/contacts not operational in VSD	1.14	2.04
VSD faults1 due to high temperature environment	10.14	26.40
Other?	0.20	0.45
Fault with stairwell doors		
Poorly fitted doors ie rubbing against door frame	6.82	7.74
Faulty1 door closure device	11.93	8.52
Door forces too high because of external environmental conditions	4.82	6.26
Faulty Door Hardware	15.00	15.00
Damaged Doors	20.00	NA
Locked Doors	8.75	2.50
Gap under Door	5.00	NA
Commissioning Performance		
Door forces less than 110N	29.29	28.35
Airflow velocity at door greater than 1m/s	19.29	17.90
Noise measurement within limits of AS1668.1	39.58	39.38
Restoration times within limits of AS1668.1	23.50	34.89
Manual fan override controls work	23.00	43.24
Other Faults		
Additional holes/leakages in stair shaft	7.88	7.22
Pressure too high in stairwell, tight stairwell	7.38	7.05
Relief on occupied floors blocked/restricted	19.73	16.14
Building itself, is too leaky for SPS	2.71	3.68

Table 5.8: Summary Survey Results for Stairwell Pressurisation System Reliability

A number of qualitative/semi-quantitative comments were received in the process of undertaking the surveys, some of these are significant comments, recurring themes received are summarised below:

- It is estimated that out the approximate population of 8,000 New Zealand sprinkler systems approximately 200 are non compliant. [O’Brien]
- Current trends is that approximately ⅓ of systems being installed are to Building Code requirements rather than full compliance to NZS 4541. Proportion higher for some occupancy groups. [O’Brien]
- Reliability concerns due to the reduction in towns main pressure though this appears to have stabilised at least in main centres. [Various]
- Back flow prevention valves are not monitored and may not be physically secure. Introduces a significant threat to water supply reliability. [Various]
- Certification and compliance regime is having an increasingly positive effect on quality of system installations and commissioning. [Various]
- Approach to alterations varies from place to place. In some places BCA’s are requiring independent certification in others the contractor is self certifying. Recertification generally only becomes a requirement if there is a panel upgrade or a new zone added to the system. Certification only includes the new work not the existing installation.
- Importation of counterfeit components is a potential issue [O’Brien]
- Floor isolation valves being tampered with is not uncommon [Various]

- Concerns raised about thoroughness of testing and level of understanding of the testers. Comment that testers do not analyse results and identify issues “they just tick the boxes”. [Various]
- View that various aspects of testing not being carried out consistently across the industry. For example sample testing of smoke and heat detectors, testing of sounders, testing of floor isolation valves assemblies.
- Concern over accidental activation can lead contractors to isolate whole system rather than partial isolation so they can be confident they are not working on a live system. [Various]
- Concerns raised that there may be issues with reliability of brigade signalling under current arrangements particularly with respect to paging messages being sent through to contractors. [Various]
- Concerns that systems (alarms) being connected whilst still have faults. [Various]
- Industry opinion is that stairwell pressurisation system reliability is primarily dependent on the quality of installation, commissioning and maintenance. [Various]

Fire Protection Inspection Systems (FPIS) Statistics

Fire Protection Inspection Services carry out the majority of fire sprinkler system inspections in New Zealand, both commissioning inspections and ongoing surveys. For systems installed to NZS 4541 surveys are carried out once every two years. Faults on systems are recorded in reports and the reports catalogued into a database.

FPIS Statistics were analysed from the current database. The number of fault items recorded in the database was 84,137. These fault items were analysed and the results are summarised in the table below, note the code glossary supplied by FPIS did not match code items and some code items are described based on the typical items coded under the code number. As would be expected with a database of this size there were a significant number of miscoded entries, uncoded entries and apparent duplicate entries.

Code	Code Description	Total # sites	Total # occurrences	Average Instances/site
0	Uncoded	Not measured	2959	Not measured
1	Water Supply	0[10]	0	0
2	Unprotected Areas	979	4388	4.5
3	Concealed Space Protection	14	45	3.2
4	Cupboard and Wardrobe Protection	188	820	4.4
5	Storage heights exceeded	406	1009	2.5
6	Racks without bulkheads	89	163	1.8
7	Inadequate Shelf protection	67	173	2.6
8	Racks over width	126	231	1.8
9	Inadequate sprinkler clearance (ordinary hazard)	306	1733	5.7
10	Inadequate sprinkler clearance (high hazard)	70	103	1.5
11	Storage clearance over Lundia	22	90	4.1
12	ESFR sprinkler clearance	7	14	2.0
13	Storage Height limitation signs	9	10	1.1
14	Damaged sprinklers (includes painted over)	654	2923	4.5
15	Exposure Hazard (building)	670	1620	2.4

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[10] Although not recorded against this code a number of water supply non compliances were noted as uncoded or against other codes. The total number of these has not been fully assessed but is estimated as at least 2 uncoded entries and 1 miscoded entry.

16	Exposure Hazard (Other item)	44	49	1.1
17	Inadequate separation/exposure hazard	28	28	1.0
18	Valve room remedial including block plan information	2763	34379	12.4
19	Pump remedial items	494[11]	6676	13.5
20	Fire door faults	13	13	1.0
21	Missing or incorrectly installed floor isolate valves	50	165	3.3
22	Missing or incorrectly installed flow switches	55	94	1.7
23	Sprinkler spacing too high (typically distance off the wall)	911	2209	2.4
24	Sprinklers too close	354	935	2.6
25	Sprinklers baffled	632	2855	4.5
26	Sprinklers baffled (residential sprinkler)	62	156	2.5
27	Sprinklers >50 years old	14	25	1.8
28	Missing or inadequate FSI	51	166	3.3
29	Items attached (e.g. cabling) to sprinkler pipe work	530	1351	2.5
30	Corrosion of sprinkler pipe work	336	847	2.5
31	Inadequate bracing of pipe work	719	3368	4.7
32	Work tables with no protection under	4	7	1.8
33	Escutcheon plate issue	850	4425	5.2
34	Missing sprinkler guards	48	62	1.3
35	Back flow prevention non compliant	8	10	1.3
36	First aid fire fighting equipment non compliant	589	1452	2.5
37	Ceiling tile broken, missing or require sealing	554	2374	4.3
38	Seismic bracing recommended	953	1678	1.8
39	Water supply strainers	3	3	1.0
40	Additional remarks	792	2442	3.1
41	System not brigade connected	80	139	1.7
43	Redundant sprinklers installed	90	174	1.9
44	Standard response sprinklers installed in sleeping areas (ELH)	86	99	1.2
45	Standard response sprinklers installed in sleeping areas (OH)	14	19	1.4
46	Partial protection	98	162	1.7
47	Unprotected stairwell	5	8	1.6
48	Inappropriate sprinkler type	137	453	3.3
49	BCF fire extinguisher installed	16	41	2.6
50	Expanded plastic (exposed) or other material with high spread of flame index	11	15	1.4
51	Water supply issues	521[12]	975	1.9
58	Non compliant with Building Code Requirements	2	2	1.0

Table 5.9: Indicative Layout for Query Table Against FPIS Database

Based on an estimated number of sites in the database this yields the following % occurrences for each item coded (items not relevant to office/apartment occupancies have been removed). The percentages presented do not account for the fact that not all sites will have the potential for the fault identified. Fir example not all sites have rack storage so the % indicated for rack storage faults will underestimate the prevalence of this fault for storage occupancies.

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[11] At least one of these included pump start issue which is considered to indicate water supply failure

[12] Out of this there were 175 references to inadequate water supplies

Code	Code Description	% Occurrence
0	Uncoded	0.0%
1	Water Supply	0.0%
2	Unprotected Areas	28.0%
3	Concealed Space Protection	0.4%
4	Cupboard and Wardrobe Protection	5.4%
7	Inadequate Shelf protection	1.9%
9	Inadequate sprinkler clearance (ordinary hazard)	8.7%
11	Storage clearance over Lundia	0.6%
14	Damaged sprinklers (includes painted over)	18.7%
15	Exposure Hazard (building)	19.1%
16	Exposure Hazard (Other item)	1.3%
17	Inadequate separation/exposure hazard	0.8%
18	Valve room remedial including block plan information	78.9%
19	Pump remedial items	14.1%
20	Fire door faults	0.4%
21	Missing or incorrectly installed floor isolate valves	1.4%
22	Missing or incorrectly installed flow switches	1.6%
23	Sprinkler spacing too high (typically distance off the wall)	26.0%
24	Sprinklers too close	10.1%
25	Sprinklers baffled	18.1%
26	Sprinklers baffled (residential sprinkler)	1.8%
27	Sprinklers >50 years old	0.4%
28	Missing or inadequate FSI	1.5%
29	Items attached (e.g. cabling) to sprinkler pipe work	15.1%
30	Corrosion of sprinkler pipe work	9.6%
31	Inadequate bracing of pipe work	20.5%
32	Work tables with no protection under	0.1%
33	Escutcheon plate issue	24.3%
34	Missing sprinkler guards	1.4%
35	Back flow prevention non compliant	0.2%
36	First aid fire fighting equipment non compliant	16.8%
37	Ceiling tile broken, missing or require sealing	15.8%
38	Seismic bracing recommended	27.2%
39	Water supply strainers	0.1%
40	Additional remarks	22.6%
41	System not brigade connected	2.3%
43	Redundant sprinklers installed	2.6%
44	Standard response sprinklers installed in sleeping areas (ELH)	2.5%
45	Standard response sprinklers installed in sleeping areas (OH)	0.4%
46	Partial protection	2.8%
47	Unprotected stairwell	0.1%
48	Inappropriate sprinkler type	3.9%
49	BCF fire extinguisher installed	0.5%
50	Expanded plastic (exposed) or other material with high spread of flame index	0.3%
51	Water supply issues	14.9%[13]
58	Non compliant with Building Code Requirements	0.1%

Table 5.10: Percentage of Sites with Reported Fault Condition

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[13] 5% occurrence of inadequate supplies.

Although any fault could impact the performance of the system the ones likely to have a significant effect (for apartments and offices) are where the water supply is impaired, where sprinkler activation might be significantly delayed or where the area of fire start is unprotected.

Inadequate water supplies account for approximately 5% of the faults (a mean of 3% was indicated from surveys). In general these faults are performance below the design requirement so would not be expected to result in catastrophic failure. Based upon the FPIS data approximately 0.1% of water supplies would be expected to be unable to perform effectively and a further proportion of marginal supplies might fail. If 10% failure for marginal supplies were conservatively assumed (this is considered conservative since the overwhelming majority of fires require flows that are a fraction of their design flows). Then this would give an estimated water supply failure rate of the order of 0.6%. This is consistent with survey results which indicated mean values for water supply isolation and impairment of 0.17% and 0.5% respectively.

Unprotected areas (code 2) appear to be more common in the FPIS statistics (surveyed values indicated a mean 6% occurrence of unprotected rooms which is consistent with non-FPIS statistics). These non compliances for apartments are primarily due to unprotected cupboards and wardrobes (which should be coded under 4). If the fire started in these locations then there is a possibility that the system would fail to maintain tenability. It is extremely difficult to estimate the loss of efficacy due to this. Certainly the fire scenarios involving the unprotected location constitute a small fraction of the possible fire scenarios (between 0.3% and 3% depending on interpretation of US data). If it is assumed that 1.5% of apartment fires start in (potentially unprotected) storage areas and that the efficacy is significantly compromised (50% for the sake of argument) then the resultant failure rate would be 0.2%.

A net failure rate for the surveyed population of NZ sprinklers might be expected to be of the order of 1% (i.e. a success rate of 99%). This would be expected to be a conservative upper bound with the true effectiveness of the system being reduced by (for example) smouldering fire scenarios, system unavailability, fire following earthquake, etc.

It is interesting to note the significant proportion of systems where bracing/seismic strengthening is raised as a fault issue.

Given that the FPIS data has not been broken down into various occupancy types it is difficult to compare this statistic with the value from other sources.

Other Sprinkler Statistics (non FPIS)

Sprinkler survey statistics have been obtained for 1,293 New Zealand sprinkler system surveys between 1999 and 2007. Multi-storey offices only account for approximately 10% of these surveys and apartments for approximately 3%. The remaining building stock was a mixture of retail, crowd occupancy, healthcare, education and some industrial. Statistics are presented in table 5.10 giving the breakdown by fault or issue type for office buildings, apartment buildings, and all building types. Detailed summary statistics including annual breakdowns are given in Appendix E.

Fault/Issue	Office	Apartment	All Building Types
Inadequate Supply	1.97%	2.38%	1.70%
Signalling Fault	1.32%	2.38%	1.08%
Fire Service Inlet	0.66%	0.00%	1.01%
Flow Switch	0.00%	0.00%	0.23%
Floor Isolation	0.00%	0.00%	0.08%
Street valve	3.95%	0.00%	0.62%
Pump performance	2.63%	0.00%	1.47%
Pump Start	3.29%	4.76%	1.24%
Sounders	0.00%	0.00%	0.15%
Anti-Interference Gear	2.63%	0.00%	0.85%
Isolated	0.66%	0.00%	0.23%
Pressure switch	0.00%	4.76%	0.15%
Unprotected Areas	1.97%	9.52%	2.48%
Residual	90%	76%	89%
Minor Faults or No Faults	94%	76%	89%

Table 5.11: Summary of Sprinkler System Surveys (1999 – 2007)

Inadequate supply included marginal supplies and indicated a system not meeting (or being close to limits of) design performance. This may be due to town main water supply changes.

Signalling fault include defect signal and fire signal faults and communication faults through to service providers.

Fire Service Inlet faults included the FSI not being present or being damaged or blocked.

Flow switch was non operation of the switch (mechanical) or switch not signalling to the panel.

Floor isolation was single case identified in the records of a floor isolation valve being closed.

Street valve issues are generally either difficulty in locating the valve maybe due to it being covered over or difficulty in accessing the valve because of it being in a hazardous position. It does not in itself represent a failure mode but does mean that the performance of a dual supply town main system is sometimes not fully tested as per the requirements of the Standard. Because it does not constitute an immediate threat to system performance the final line of table 5.10 showing no faults or minor faults does not include this factor.

Pump performance issues cover a number of faults both in terms of ability to provide adequate pressure as well as issues which might impact on future reliability or life expectancy of the pump, for example issues with cooling water arrangements. These may or not result in a reduction in the immediate system effectiveness but certainly increases the risk of failure.

Pump start covers those situations where there were problems getting the pump started. The estimate is conservative in as much as this count includes situations where pump finally started but are indicative of potential for failure.

Sounder failure rates are low but it needs to be remembered testing of sounders is not a normal part of fire sprinkler surveys so would only be discovered under unusual circumstances.

Anti-interference gear makes no discrimination between electrical and mechanical devices. Based on survey responses it would be expected that mechanical devices are less reliable than electrical.

Isolated refers to systems being isolated from their water supplies. This is clearly a worst case scenario for sprinkler system reliability.

Pressure switch issues were reported relatively infrequently compared with anecdotal comment. Given infrequency issue would be expected to be more than just the settings being out of range and could represent a critical failure mode. If this is the case there is a concern that this was a relatively high proportion of apartment building cases but given the low sample size it is difficult to have confidence in this result.

Unprotected areas for office and apartment buildings were typically small areas. Common issue for apartment buildings seemed to be non protection of cupboards and wardrobes. Differences in the reported values between this data and FPIS may be due to different interpretation of the requirements under the Standard.

The percentage of systems with only minor faults represents a lower bound for reliability. For the systems with non minor faults many of these would not result in system failure, the key exception clearly being that the system is isolated. For those that could result in system failure for example inadequate water supply there is a high likelihood the system will still perform effectively. Based on the simplistic assumption that 1 in 10 possible failure causes results in failure then the indicative reliability of the systems would be of the order of 99% which is consistent with the results from the FPIS data.

6

Bias and Variation in the Data/Analysis

Much of the literature for fire protection system reliability relies upon data collected in the field by fire service personnel responding to fires and fire protection system contractors responding to system faults and activations. It is not practical to eliminate bias in the data collected in this way.

One well known bias is the tendency for any such dataset to over-represent large fires or significant faults. Small fires are more likely to be dealt with without the involvement of the fire brigade. Minor faults may not warrant the effort of comprehensive reporting.

A proportion of large fires will become large because of failures of systems earlier in the fires development. If the failure is identified then this would tend to over-represent the proportion of failures in the population of fire events. It is possible that large fires may destroy any evidence of system failure but this is less likely for monitored systems in commercial and residential developments than it is for domestic systems.

Categorising success or failure of fire protection system may be done in quite different ways from one dataset to another. One measure may simply be whether the system operates, another may be whether the system performs as per its design objective (this can be further split into whether this is a performance objective or a prescriptive requirement), another may be the effectiveness of the performance. These relate to the different component parts of fire system effectiveness. The first measure is a measure of simple operational reliability, the second of the system efficacy and the third of its effectiveness. Which measure is adopted would have a significant effect on the data. This is not of concern if it is clear what the basis was, however unfortunately often it is not clear.

Measurements of operational reliability tend to come not from fire statistics but from field data on system performance. These may capture information on incipient failure conditions, non-critical fault conditions and critical fault conditions. It may not be clear from the data what is being presented. There is also some subjectivity in assessing which category any particular fault condition fits into. Fire data may be used to infer reliability information if it can be determined that a failure to operate occurred. This may be direct evidence for example an isolated system, mechanical failure, system operating on arrival, etc., or indirect evidence, for example non-receipt of brigade calls, witness accounts, etc. It is possible that a system may operate effectively as an alarm but not call the brigade due a problem with this sub-component of the system.

Measurements of whether the system has performed as per the design objective generally comes from fire statistics with some data being available through the fire protection contractors. The data from the fire statistics tends to be focussed on the performance outcomes, for example did the system alert the occupants? Did the system control the fire? This may be difficult to assess if there are no witnesses to the fire and the fire itself has destroyed evidence of the performance of the system. Even without destruction of evidence it is not often possible to determine accurately at what stage of fire development a detector activated. Sprinkler system performance can generally be recorded if the sprinkler has extinguished or controlled the fire and from this the inference made that the system performed as designed. Forensic modelling and experiments can be undertaken to estimate the performance of the system given the evidence from the fire scene. There is considerable subjectivity in this assessment which is compounded by the fact that the design objective of the system may not be known or understood by those recording the performance of the system. The best information on system performance comes from more detailed investigations of specific fires which can be highly informative and certainly highlights any deficiencies in standards, design practices, installation or maintenance, but does not in itself allow assessments to be made of the performance of other systems (and scenarios) which differ from the specifics of the case considered.

The performance of any fire system is also a function of the scenario. For example sprinklers will not perform well if it is a smouldering fire. Some datasets identify specifically if the fire was too small to operate the detector. This is highly subjective. It also does not consider the possibility that as a fire grows the poor performance or even failure against design criteria at an earlier stage of the fire is masked by the system response as the fire grows in size.

In a data set it may not be clear if there has been a conscious or unconscious effort to screen out from the failure statistics those cases where the scenario was outside of the design scenario for the fire protection system being considered. For sprinkler systems for example are cases where storage was over limits, areas unprotected, etc., counted as failures? Where this screening has occurred it may tend to present optimistic data for system effectiveness when compared with the general population of systems. Data from the fire protection industry is typically screened in this manner with cases where systems have not performed to their design basis being presented as successes if the fire scenario was outside their design basis, the classic example being a sprinkler system overwhelmed because of storage exceeding the occupancy design basis for the system.

The effectiveness of systems comes from statistics on fire outcomes. Much of the data presented from fire service statistics is of this form and the attempts made to extract out the contribution of reliability and efficacy to the overall effectiveness varies widely. Effectiveness is often measured in terms of the impact of the system on loss of life/injury. Some data has been captured on extent of fire spread and this can also be correlated to fire systems. The data is very broad and relies upon the averaging out of variations in the data to obtain a representative measure of the effectiveness of various systems types. It is very difficult with this multivariate type analysis to be confident that the effect you are measuring is not being biased by some other aspect of the data. The fire protection systems are not distributed randomly in the population but are themselves correlated to construction type, occupancy, socioeconomic factors, building age, geographical location, etc. Their testing and maintenance will likewise be dependent on factors beyond the system itself.

Another complication is that there may often be multiple systems installed and this may not be clearly represented in the data. Some combinations may be relatively independent whereas others may have a high degree of dependency.

The effectiveness of systems may also be expressed in a variety of ways, it will by its nature be outcome focussed; lives saved, injuries saved and reduction in fire loss.

Trends in the Data

The data analysed for FPIS only covered the last 2 years so no meaningful trends could be established. The other data sets were too limited in size to be meaningful.

From the literature survey there is conflicting views on trends with some authors arguing (Koffel) that the data indicates decreasing reliability whilst others argue for improvements in performance being indicated in the data.

7

Effectiveness and Fire Engineering Design

Introduction

To give context to the analysis of fire system effectiveness presented later in the report this section discusses the importance of effectiveness when QRA is used as the basis for fire engineering design.

Using Effectiveness in Design

The effectiveness of a fire protection system depends on its reliability and efficacy. The reliability itself is a combination of availability and on-demand reliability. Each of these in turn depends on other factors. Figure 7.1 below shows a simplified arrangement of dependencies.

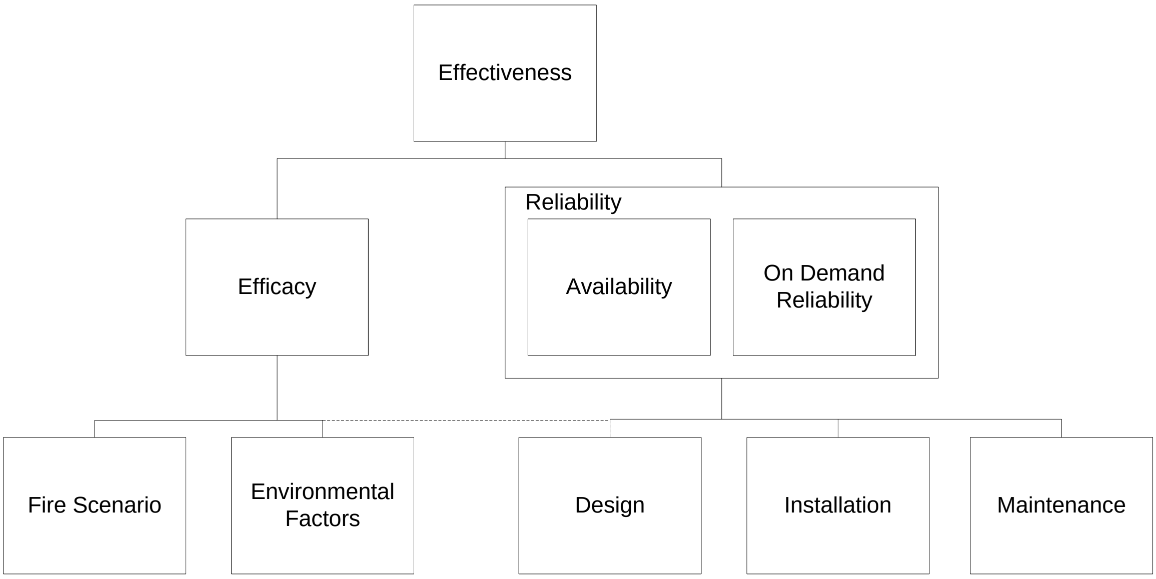

Figure 7.1

When even this highly simplified structure is considered it can be understood that representing the effectiveness of a given type of fire protection system by a single effectiveness value (‘generic’ value) or even a single effectiveness distribution is a highly abstract simplification.

Generic Values for Effectiveness

Generic values assume a single value or fixed distribution for a given system type (or range of design types). They do not usually differentiate between systems of the same type though they could in principal.

The benefit of ‘generic’ values of reliability is in their ease of use. If they are appropriately conservative they will allow conservative design in terms of measurement against benchmark values of risk. For example if a (relatively) low reliability were to be assigned to a sprinkler system and an analysis undertaken that then demonstrated that the loss of life were below some societal accepted risk tolerance then this could be used for the basis of acceptance of a design approach. The generic value in this case is not representing what is believed to be the ‘real’ effectiveness of the system but a lower limit which has a high level of confidence that the ‘real’ effectiveness is somewhere above this value. The down side of the approach is that it is likely the system will be over engineered and it does not allow one to take account of differences with a generic design type.

When comparing different design alternatives using generic values it is difficult to know whether the comparison is a fair one. The research literature and statistical data, in general, does not identify the confidence in the values being used or give any quantitative understanding of the factors which will change a generic value. If a design study were to compare a sprinkler system and a smoke detector system for example it would not be possible to predict which generic value was more or less conservative than the other for the case being considered. The tendency in these situations is to favour the status quo, i.e. generic values are used (manipulated) to give an overt bias to the accepted design approach. This may of course mean the large scale rejection of design approaches which are more effective than the ones being accepted.

Use of generic values with a continuous distribution (or multiple discrete values) allows some account to be taken of the uncertainty in the ‘real’ value. This approach is likely to result in a fairer estimate of the absolute risk or of comparative risk to a base case. This is particularly true when there is large uncertainty associated with a specific design option which if the ‘worst case’ single point value were used would lead to over conservatism in design or misidentification of the most reliable approach.

The simplest form of distribution is a uniform distribution where the same probability is assumed for all values in the range between the minimum and maximum values. This distribution is appropriate where the maximum and minimum represent values which are credible as probable values.

One common approach to assigning distributions is to assign a minimum credible value, a maximum credible value and a probable value. In this case a continuous distribution may then be established by assuming a 0 probability outside of the minimum-maximum range and assuming either a triangular (linear) distribution or a PERT distribution (non-linear). The triangular distribution is the simpler of the two but tends to overemphasise the tail of the distribution and underestimate the area close to the probable value. This is not to say that the PERT distribution is more representative than the triangular distribution for all cases. There are also a number of modified PERT distributions which allow greater control over the shape but use of these is unlikely to be warranted unless there is evidence of a particular distribution form which is not well approximated by a PERT or triangular distribution.

Effectiveness Derived from Component Measures

If the efficacy, on demand reliability and availability can be determined then the effectiveness can be estimated. This approach has the benefit of greater clarity of the factors influencing the effectiveness and allows a more flexible approach. It does however require specific information for each factor and this may not be readily available.

Efficacy

The efficacy itself is not well understood for most fire protection and fire scenario combinations. Most of the data available is for overall system effectiveness or for component reliability, particularly operation on demand. To determine efficacy it is generally necessary to consider the factors impacting on the system efficacy and account for these together with known data and expert opinion to estimate a measure of efficacy.

For the purposes of considering the effectiveness of the fire protection system the efficacy only relates to the performance of the fire protection system itself. The system does not include consideration of tenability and human response. On this basis a heat detector and smoke detector system for example could have comparable efficacy for a given fire scenario but may have quite different expectations in terms of the level of life safety provided.

Fire Scenario

The effectiveness of the fire protection system can be refined by consideration of the efficacy factors. These are primarily a mixture of scenario and environmental factors with interdependencies on the nature of design, implementation and maintenance of the system.

A simple example of the impact of efficacy factors is consideration of the effectiveness of fire protection systems for different fire scenarios, for example smoldering fires, flaming fires and post-flashover fires. The reliability of a system is the same for all of these scenarios but the efficacy can vary widely. The table below summarises some of the effectiveness values taken from the Australian Fire Engineering Design Guidelines which include implicit consideration of the effect of scenario on system effectiveness.

System	Smouldering Fire	Flaming Fire	Post-Flashover Fire
Sprinkler System	0	90	95
Heat Detector	0	90	95
Smoke Detector	70	80	85

Table 7.2: Effectiveness of Systems for various Fire Conditions

These values are presented as point values but the approach could equally be applied to distributions.

If for the design being considered it is clear that a particular fire 'type' dominates then this value or distribution could be used. In practice a range of different fire scenarios could be expected and in this case the resultant value or distribution has to be averaged across the various scenarios. This is the approach taken in the FireCAM software.

Certain systems may have inherent limitations as to their effectiveness for certain scenario types. Examples include:

- Fires involving accelerant
- Fires within an escape route
- Fire within a pressurised stairwell
- Low heat release (smoldering fires)
- Clean burning fires

If the efficacy of the system is being considered across all scenario types then consideration needs to be given to the likelihood of these type of scenarios as well as the more conventional scenarios. There is data available for the relative frequency of each fire scenario from sources such as NFIRS and FIRS. For this work the emphasis will be on three specific fire scenario characteristics.

Smouldering or flaming fire
Shielded or unshielded fire
Fire in concealed space or in open space

It is possible, in principle, to analyse the efficacy of the system to gain understanding of the impact of the fire scenario. Design software for stair pressurisation systems for example allows the impact of environmental conditions (including the fire) to be evaluated. Computational fluid dynamics software enables estimates of device response to heat or smoke, or the movement of smoke through a building. This is different to using these analytical approaches for design where we might assess the time for a system to respond, the tenability conditions or control of fire growth. Analysis of efficacy is a sensitivity study considering the impact of environmental variables (including the fire scenario) on the outcome response of the system. Given the uncertainties in the input data and the limitations in the models themselves it is not appropriate to rely on this approach to predict efficacy but it does provide valuable supporting information.

It is assumed that variables which affect the fire scenario, for example the ventilation conditions in the fire compartment, can be considered implicitly and independently in the scenarios used to derive the efficacy of the fire protection system(s). These variables will also (typically) be considered in any tenability analysis and the use of fire scenario variables in the tenability analysis does not necessarily mirror the use in any consideration of the fire scenario on system efficacy. Ideally full consideration would be given as to the range of fire scenario variables for both the efficacy and the tenability analysis however in practice this is unlikely to be achievable or warranted given uncertainties in information. (Double counting)

Environmental Factors

Beyond the fire scenario itself there are a number of general environmental factors (those factors which are natural variables or outside of the control of the fire protection system design) which may impact the efficacy of the design.

A more conventional environmental factor is air movement. This may be internal or external to the building. Sprinkler system efficacy may be impacted by air handling equipment as has happened in New Zealand with a system having an excessive number of sprinkler heads operated due to the hot gas from the fire plume being blown across the underside of the ceiling. Another example is the concern over location of ventilation fans close to early suppression fast response sprinkler heads. These issues are not likely to be significant for the buildings of interest but are presented here for completeness.

For stairwell pressurisation systems wind effects and temperature effects impact on the efficacy of the design. Tightness of construction is another significant environmental factor for pressurisation systems. Tightness of construction cannot necessarily be determined at the design stage as it not only depends on the material being used but also on details of implementation and quality of workmanship. It therefore needs to be considered as a variable in the analysis of system efficacy.

Design Considerations

Designing for efficacy with a given system type can be achieved in a two main ways:

- Selection of technology

- Detailed design choices within permitted ranges

The first of these is commonly applied with smoke detection systems where a specific technology type (aspirating, photoelectric, ionisation, etc) is selected based upon achieving efficacy for the fire scenario(s) of interest.

The second of these for example could be decisions on detector coverage, placement and spacing (and likewise design of alerting systems). All of which will have a potential impact on system efficacy.

The former has been considered in the analysis in the report the latter has not, primarily because of limited data on the impact of these design variables on efficacy.

Installation and Maintenance

Installation relates to efficacy as poor installation practice (the classic example being poor detector placement) will have a direct impact on efficacy.

The impact of maintenance on efficacy is predominantly those aspects of poor maintenance which do not lead to complete failures but rather a degradation of system performance. For example dirty detectors, fouling of pipe, water supply degradation. Where these are of such magnitude that they render the system ineffective they can be observed in the failure statistics. Where the degree of degradation is less, it is extremely difficult to quantify the impact this has on efficacy and thus on overall system performance.

Broader View of Efficacy

For looking at fire system effectiveness we are defining our system as the physical system itself and its direct functions. We are interested in the impact the fire scenario and environmental variation has on system performance but are not in our analysis considering the tenability conditions and human response as part of our ‘system’. In a broader analysis for fire engineering design these factors will clearly be of interest and in quantitative assessment the tenability analysis and human response will often be factored into an event tree analysis using a limit state approach (this is discussed in more detail in Section 10).

For this broader analysis a key determining factor of the wider ‘efficacy of systems’ is the vulnerability of those people exposed to the fire. The efficacy of a system will be different for a kindergarten than it would for an apartment building. To some extent this issue is accounted for in the design process when tenability is considered. The designer may assign a slower movement speed to certain groups for example, or even allow for delayed response. They are unlikely however to set more conservative tenability criteria, or allow for a higher risk of non optimum decision making. By considering the efficacy of the system with regard to the vulnerability of the at risk group, allows a means of accounting for these factors and also makes comparison between systems transparent based on a quantified risk measure.

The means of escape from the building can be considered as an environmental factor in the performance of the fire protection system or as a component part of the overall fire protection system. The means of escape provisions will clearly influence the tenability analysis. They will also alter the efficacy of the fire protection system.

Availability

The availability (and consequently the unavailability) of fire protection systems is the proportion of time for which the system or critical components and subsystems are not available. Unavailability could be for a number of reasons:

- Unavailability of utilities on which they are dependent (e.g. water, power) which could be due to planned or unplanned outages of supply.
- Unavailability of component or subsystems due to failure and subsequent time needed to repair. (Note: the probability of undetected failure is factored into the reliability on demand for components and sub-systems and often this is more significant than the unavailability as the repair time is shorter than the potential detection time).
- Unavailability due to testing and maintenance activities on the system.
- Unavailability due to system being isolated for building work or alteration to the system (this could include repair and reinstatement following fire).

The fire scenario in general has little impact on availability; either the system is working or it is not. There are special circumstances when the scenario may be important notably when only a certain area of the system in impaired (for example a fire alarm zone or an isolated floor) in which case whether the system is available or not is fire scenario dependent.

Environmental conditions can impact on reliability the obvious example being potential for freezing of pipe work in mountainous areas and parts of the South Island.

Design Considerations

Designing for availability consists of the following types of strategies:

- Provide backup for utility supplies. This may be by duplication of supplies, for example multiple feeds for mains power or dual water supply connections. It may be by providing fully independent backup for example generator or battery backup for power or tank, and pump backup for water supply.
- Redundancy of critical components and subsystems to reduce downtime due to component failure. These may be in parallel service or able to be rapidly swapped into service. Clearly selection of technology and designs which have lower failure rates reduces unavailability due to this cause and more importantly (generally) reduces the on demand failure probability.
- Selection of technology and designs with less maintenance and testing downtime. The ‘life safety valve set’ for example achieves this by allowing the system to remain live during valve overhauls. Differing alarm technologies have differing requirements, for example heat detection versus smoke detection. Lack of thought during the design process in terms of ease of testing and maintenance can have an impact as well. For example poor provisions for drain testing, difficult access for isolation valves, cramped valve rooms and alarm panels cabinets/rooms.
- Design for zoning and sectional isolation of systems so that the system may be partially rather than fully isolated.

Installation and Maintenance

Installation quality will have a direct impact on failure rate and hence availability from this cause. Poor placement of gauges, valves, etc. can also make testing and maintenance more difficult.

Maintenance is a cause of unavailability and also acts to prevent unavailability from failures.

On Demand Reliability

The on demand reliability is a combination of two base causes. Firstly the risk that a system may fail at the moment the demand is made, and secondly that there may be a latent failure which is only uncovered when the demand is made on the system.

This will largely be due to hardware failures (mechanical, electrical) but particularly for complex systems there is a significant risk of software failure.

Fire Scenario

The fire scenario can have an impact on the on demand reliability of the system. One key example is a fire scenario following an earthquake which has been looked at by a number of authors including a New Zealand study on fire following earthquake in tall buildings by Taylor (2003). Not surprisingly various authors conclude that the reliability of the system can be severely impacted by the earthquake event. Sprinkler systems being particularly vulnerable given for the potential for loss of water supplies and mechanical damage to the system. Potential for loss of mains power and mechanical/electrical cable damage could impact on stairwell pressurisation systems reliability and also damage to doors and the stairwell integrity may impact on the efficacy of the system. Compared to sprinkler systems and stairwell pressurisation systems the loss of reliability of alarm systems following an earthquake would be expected to be less severe.

Similarly where there is potential of an explosive event in association with the fire there is a risk of damage to and hence reduced reliability of fire protection systems.

Deliberately set fires can also compromise the effectiveness of systems either by interference with the system itself; for example by isolation of water supplies or tampering with detectors, or by introducing a fire which is beyond the design capability of the system.

Environment

Reliability can clearly be affected by the operating environment. Specialised detectors, etc., are available to provide suitable levels of reliability for equipment.

For sprinkler systems water quality can be a factor in system reliability and longevity.

Design Considerations

There are various design approaches to increase on demand reliability of systems, some of these include:

- Utility backup. Provide independent backup for utility supplies. Battery backup for alarm panels, pump and tank secondary water supplies are example of utility backup.
- Redundancy. Use of parallel in service equipment or automatically swapped in equipment. Duplicating of water supplies, etc., would be examples of redundancy.
- Simplicity of design. Removing complexity can be a strategy for increasing reliability. For example use of simple software control for fire alarm systems. With a sprinkler system for example it would be more reliable to design the system so that a booster pump was not required.
- Ease of testing and maintenance. Design systems to be easy to test and maintain.

Many approaches to promote system reliability are written into the appropriate standards but these are minimum standards and it will generally be possible to improve reliability by careful consideration of the design.

Installation and Maintenance

Installation quality will have a direct impact on failure rate and hence on demand reliability from this cause. As for availability installation quality can impact on reliability as poor placement of gauges, valves, etc. can make testing and maintenance more difficult.

Maintenance (and notably commissioning) is also critical to provide for the highest levels of on demand reliability.

Approaches for the Use of Effectiveness

Information on the effectiveness (or reliability or efficacy) of systems can be used in a variety of ways in the design process. Three key uses for this information are as follows:

Absolute Risk. It can be used (with event trees for example) to estimate the likelihood of the various outcomes which can be aggregated to give an overall risk measure for example annualised probability of loss of life or the probability of a structural failure or an economic impact in $/year.
Relative Risk. It can be use to compare the effectiveness of alterative designs against one another or against a reference base case. In this case there would not need to be any absolute measure of risk of any initiating event.
Sensitivity. It can be used to investigate sensitivity of fire outcomes to component and sub-component parts of the fire safety design thus providing a basis for the focus in introducing redundancy, increasing maintenance provisions, etc.

Absolute Risk

This is useful if there is an accepted benchmark measure for tolerable risk, or in the case of economic risk if there is a basis for cost comparison. Such a benchmark may not be a single measure but may vary according the demographic.

Under New Zealand legislation there is (as yet) no accepted benchmark for acceptable likelihood of loss of life or injury. Work by McGhie (2007) has looked at risk ranking methods to provide a first order comparison of levels of life safety provided by various design classes. In principle a similar approach could be used to benchmark risk levels in absolute terms using quantitative risk analysis approaches.

Relative Risk

Relative risk can be used to either compare effectiveness of alternative design options or to measure against a specific benchmark approach. In the latter case it may be particularly difficult to compare like with like as the benchmark approach may impose a design philosophy which is quite different from the case(s) being compared. For example the benchmark case may impose specific limits on travel distances and number of exits. This requires a more complex analysis than say comparing the effectiveness of sprinklers versus smoke detection and fire separation for the same basic building design.

Sensitivity

Sensitivity studies are useful in providing insight into areas of vulnerability of a design. For a single system they identify potential improvements in effectiveness. When used in conjunction with design alternative comparison it allows an understanding of the relative robustness of alternatives and confidence in system performance.

Quantitative Risk Analysis

In this section Quantitative Risk Analysis (QRA) is briefly discussed. There are a number of sources of more detailed inform on QRA applied to fire engineering decision making including Frantzich (1998) and Barry (2002).

Quantitative Risk Analysis (QRA) is of interest to this research for three reasons:

The scope of the research is reliability data for use in QRA. To understand the most useful form

for, and limitations of, this reliability data it is necessary to consider the QRA process.
QRA methods can be used to analyze reliability itself.
Uncertainty in reliability due to lack of knowledge and natural variation in values can be quantified using QRA.

Introduction

The risk assessment process undertaken for fire risk is generally consistent with accepted risk assessment practices for example the use of NZS 4360.

Broadly acceptable levels of safety (tolerable risk) can be demonstrated in the fire safety design by one of three methods:

- Absolute risk where the achieved risk level (individual and/or societal) is measured and compared with some accepted benchmark which may either be a specific risk value or a probability-consequence curve (the classic example being the F-N curve).
- Relative risk where the risk measure for the proposed design is compared with the risk for an accepted design.
- Accepted input criteria where there is defined input criteria for the design (explicit or by validation). In this approach the risk level is implicit in the limitations in the selection of the design input criteria.

All of these have pros and cons which have been discussed by others including Frantzich.

Each of these approaches can if required include the effects of uncertainty in the variables describing the scenarios.

A fire safety system (in the broadest sense) may fail for a number of reasons which can be broadly grouped into two types:

- Natural variability. Failures may occur because of the indeterministic nature of the world. This may be seen for example in variations within the 'fire system' such as the processes leading to component failure. It may be external variations such as temperature, wind speed, the fire growth. Some of this variability would typically be incorporated into the model developed to establish the level of risk but it is not practical to account for all natural variability.
- Fundamental errors. These may be human errors such as faults in design or installation. These by their very nature cannot be specifically foreseen though they can be assumed to exist and are highly significant for fire system reliability.

When considering uncertainty there are two key types of uncertainty in any model which we may use to determine fire risk.

- Knowledge uncertainty. Our knowledge is incomplete. We can estimate what we believe is an appropriate value or distribution for a parameter in the model but there is always a level of uncertainty attached to this value. This is clearly the case for fire protection system reliability where there is considerable variation in the accepted value (or distribution) for reliability of even simple systems such as wet pipe sprinkler systems.
- Random behaviour. Even if we have good knowledge of a parameter there will still be random behaviour which will introduce uncertainty in our prediction.

Event Trees and Fault Trees

These are widely used in QRA. The discussion of these is brief, further information is available from a number of sources including (amongst others) Lees, Keey and Vesely et al.

Event Trees

Event trees are normally bimodal with each event branching to two subsequent events. The initiating event is normally a fire and each branch point represents various critical transition points until we get to an end point which may be a defined success condition (for example fire extinguished) or an unwanted condition. Each of these end points represents a sub-scenario of the event tree. The end point can be represented by a Kaplan and Garrick triplet

$$R_i = s_i, p_i, c_i$$

Where R_i is the risk associated with the branch endpoint, s_i is the sub-scenario description, p_i is the sub-scenario probability and c_i is the sub scenario consequence.

The total risk R is the set of all triplets:

$$R = s_i, p_i, c_i$$

In practice the probability and consequences will be subject to variation resulting from uncertainty and the values can be expressed as probability distributions.

$$R = s_i, p_i \varphi_i, c_i \phi_i$$

If we wish to analyse the effectiveness of fire protection systems this is the general form that is required in order to consider both reliability and efficacy (consequence related). This will be discussed further in section 10.

Fault Trees

Fault trees are used to obtain a probability of a top level outcome. They are widely used for reliability studies where system or sub-system failure is the outcome of interest. They are very powerful for structuring thought about failure mechanisms. The number of levels of the tree depends on the level of knowledge available and the purpose of the analysis. Since they do not include analysis of consequences they are not necessarily suitable for considering effectiveness of systems.

As discussed above uncertainties exist due to random behaviour and lack of knowledge. These uncertainties propagate through the event tree and fault tree with resulting uncertainties in predictions. Use of analysis can allow this uncertainty to be understood and quantified.

Further to this uncertainty the models may also be incomplete. There may be branches missing from the tree. It is difficult to account for this as it outside of the model. Some of these may be analytical but have been deliberately excluded as being outside of the scope. Common examples of this include natural hazards, terrorist attack. Human error is another area often excluded from the tree as it is difficult to incorporate. Care also needs to be taken in dealing with common cause failures, the classic example being loss of the power supply.

Unwanted Consequences

The unwanted consequences are those things that we do not want to happen. In QRA for life safety fire risk these will typically relate to potential for loss of life. This may be a direct measure such as a probability for a loss of life occurring or an indirect measure such as exceeding an established tenability criteria.

It is generally necessary to use some form of state function within the model to compare the provisions for life safety with the requirement for life safety (demand versus supply). In its simplest form this might be an expression such as:

$$G = A - R$$

Where
A is the available commodity (for example the available safe egress time)
R is the required commodity (for example the required safe egress time)
G is the measure of success for the state function

Success for example could be $G \geq 0$ for all conditions of interest. The state equation may include safety factors, for example where we double the value of R calculated in the model:

$$G = A - 2R$$

More generally there will be uncertainty associated with the model(s).

$$G = AU_A - RU_R$$

Where U_A is the uncertainty in the model for A, and U_R is the uncertainty in the model for R.

The most widely used state function for fire safety is in the time domain and is given by (for example, other representations are used):

$$G = t_a - t_d - t_r - t_m$$

Where
t_a is the available safe egress time (time from ignition at which acceptable tenability criteria are exceeded).
t_d is the time for the detector to activate and sound the alarm.
t_r is the time for the person(s) exposed to the fire to respond
t_m is the time for the person(s) exposed to the fire to move to a place of safety

Generally this is solved by calculating values for each parameter and then assessing whether $G \geq 0$. This process would be repeated for all scenarios of interest.

Sensitivity analysis and/or safety factors may be used on the parameters, a margin applied to G, or safety factors conservative assumptions used in the values used to calculate the parameters. Reliability of fire protection systems is generally not accounted for in the analysis except there may be some consideration given to the consequences of system failure

Normally the available time would be calculated on the basis of tenability criteria. These do not represent conditions that would necessarily be expected to cause loss of life but reflect conditions which we as a society we will tolerate (as evidenced by acceptance through regulation) as being critical and which we are unwilling to expose people to as part of a design. This is due in large part to the knowledge uncertainty around tenability given the potential variation of vulnerability in the population.

The fire safety systems such as sprinkler systems and alarm systems do not (generally) have any specific requirements in terms of performance under a QRA approach. Expectations of performance are given in some Standards documents. In principal these could be used with a state function to give a measure of fire protection system effectiveness. In practice the acceptability of system performance can only be considered in the overall context of the fire risk model. The exception to this is stairwell pressurisation systems which under relevant Standards (for example AS 1668) do have specific acceptance criteria which can be used as the basis for risk analysis of the system itself, this approach has been investigated by Fazio (2007).

Referring back to the fire safety state function the performance of the fire safety system has in impact on various parameters making up the state function as summarized in Table 7.4.

System	t_a	t_d	t_r	t_m
Sprinkler system	Y	Y	Y	Y
SPS	Y	Y	Y	Y
Alarm	N	Y	Y	N

Table 7.4: System type relationship to time based state function components

The effectiveness of the system depends on reliability. For a complete analysis it is not necessarily sufficient to include the reliability of the system as a measure on the event tree branch but it also needs to be incorporated into the state function. This reflects the fact that expressing fire protection systems as binary systems, succeed or fail, is a simplification. The efficacy of systems can range from 0% to 100%. This is discussed further in section 100.

Selection of Values

In a standard analysis where QRA is not being used the normal design approach is to use conservative design values with the state function. If non conservative values are used they are presented as part of a sensitivity analysis.

For QRA two approaches can be used.

- Use conservative values including values for reliability (i.e. low reliability) of fire protection systems. This would lead to a conservative prediction of the level of risk. The level of conservatism depending on the sensitivity of the risk prediction to the value of the input variable. The reliability of sprinkler systems for example has a significant impact on the overall risk level as evidenced in the work of Enright (2003), Porter (2005) and others. When considering absolute risk this may be appropriate as long as it factored into the decision making process. When dealing with relative risk however the use of conservative values could lead to erroneous results by distorting the relative value of different design approaches (or at best masking them).
- Use best estimates (most likely values). This would give most likely risk prediction which may not be conservative but for relative risk prediction would be expected to give a more representative result than using conservative values.

For either approach the effects of uncertainty can be included.

Sensitivity Analysis

In the simplest cases it is possible to define the model (or sub model) with an equation. For example the detection time as a function of fire size. In this case the sensitivity analysis can be conducted explicitly.

For more complex models regression analysis is necessary. This may be achieved by methods such as least squares fit. For non linear relationships simple transformation to linear form may be possible (for example by taking logarithms) or polynomial curve fits may be used.

Response surface methods may be used to correlate across a range of variables and this can provide an alternative to numerical sampling techniques.

With the above techniques it is necessary to include any effects due to fire protection system effectiveness into the regression analysis.

Describing Variables as Distributions

Variables may be described as distributions to account for random behavior or because of knowledge uncertainty.

Distributions can be opened or bounded. By its nature reliability is bounded taking values between 0 and 1. Risk is ≥0 and unbounded at its upper limit.

There are 3 commonly used presentations for distributions:

- Probability Density Function (PDF). This shows the distribution of the probability as a function of the value of interest. For any given probability value the function returns the contribution at that value.
- Cumulative Density Function (CDF). This shows the cumulative distribution of the probability so for any given probability of interest the function returns the fraction of probabilities which fall below this value.
- Complementary Cumulative Density Function (CCDF). This shows the inverse cumulative distribution of the probability so for any given probability of interest the function returns the fraction of probabilities which fall above this value.

Variables may be independent or dependent of other variables in the model. The correlation coefficient (Ranging between ±1) giving the strength of the relationship.

For fire protection system reliability any of the distribution presentations may be used depending on the application. Reliability of fire protection systems is considered an independent variable. The efficacy of the system may not be independent though it can be regarded as such for many applications.

The distribution of any variable may be inferred from data or from understanding of the physical processes affecting the variable. In the former case large datasets are required to provide good correlation between the assumed distribution and the real distribution. In the latter case it is the reasonableness of assumptions and the level of knowledge of the system which will determine the correlation between model and reality. In fire safety it is not uncommon that the available data is limited and the limited data needs to be combined with other knowledge (using Bayesian approach) to provide the best estimate of the distribution. Even with these approaches the knowledge uncertainty in fire distributions is often large and unfortunately subjective estimates are widely relied upon.

In the area of reliability the distribution of variables is based upon the following information summarised in Table 7.5. None of the data sources identifies a useful form for the distribution (not surprisingly given the reliance on incident data). Where variation does exist it is between different types of systems rather than variability with a type. Taking multiple data sources allows an assessment of possible ranges of reliability.

Variable of interest	Data	Analysis	Uncertainty
Sprinkler System Reliability	Fire Service Statistics	Statistical	High due to variation in basis, incompleteness and applicability.
	Component failure rates	Fault tree models	High due to limited component data and process industry origins
	Maintenance/survey records	Event and Fault Tree models	High
	-	Expert opinion	High
Alarm System Reliability	Fire Service Statistics	Statistical	High due to variation in basis, incompleteness and applicability
	Component failure rates	Fault tree models	High due to limited component data and process industry origins
	Maintenance/survey records	Event and Fault Tree models	High
	-	Expert opinion	High
Stairwell Pressurisation System Reliability	Fire Service Statistics	Statistical	High due to variation in basis, incompleteness and applicability
	Component failure rates	Fault tree models	High due to limited component data and process industry origins
	Maintenance/survey records	Event and Fault Tree models	High
	-	Expert opinion	High

Table 7.5: Knowledge uncertainty for fire protection systems

A common approach for establishing a distribution for variables associated with fire risk assessment is as follows:

- Establish minimum and maximum values. For reliability this is often subjective. Reported incident data provide some basis with a a degree of subjective interpretation based upon the scope for which the reliability data is being considered. For example the reliability you might expect for wet pipe sprinkler systems in New Zealand would be expected to be different to the reliability of dry pipe systems in the United States. There may also be the need to identify efficacy factors where these would alter the reliability used. Physical limits can be used where these can be inferred. For example (likely) reliability of water supplies may establish a practical upper limit for sprinkler system reliability. It is harder often to set a lower bound without relying on subjective approaches. Use of expert opinion and formal approaches such as Delphi Groups can be used to assist.
- Once bounds are established the most likely value is selected. In the absence of any other information the value may be selected as the arithmetic or geometric mean of the lower and upper bounds. If there is a basis for assuming a particular distribution type this may assist in selecting the mean. For reliability of systems the distribution is often considered to be skewed with the most likely value being closer to the upper bound. This is a consequence of the likely value for many system types being considered (relatively) close to the upper bound but a significantly lower bound being provided to cover the possibility (knowledge uncertainty) of lower reliability systems.
- Select the distribution parameters. Typically this would be the standard deviation but include higher order distribution parameters. It may not be possible to select meaningful parameters for reliability of fire protection systems. In this case the distribution parameters are selected they will be subjective based on for example a number of standard deviations between the mean and the bounds.
- Select a distribution form. The simplest form would be uniform which is appropriate for a fully random process or where the knowledge uncertainty limits the ability to establish a most likely value. Triangular distributions are commonly used as are PERT distributions which are

similar to triangular distributions but place more emphasis on the most likely value. All of these distributions are naturally truncated and the upper and lower bounds. The normal distribution may be appropriate. The log normal distribution is used where there are high levels of uncertainty and is representative of a system derived from a large number of normally distributed input variables which may be a reasonable approximation for fire protection system reliability.

Quantitative Methods

QRA methods may be applied using the knowledge of probabilities and consequences, the latter being quantified using a state function (together with the event tree sub-scenarios), the former being developed using event tree and fault tree methods.

The approach varies according to whether:

- The system can be modelled analytically or requires computer models (for probability/consequence)
- How uncertainty is to be handled
- The extent of the analysis
    - Societal and/or individual risk
    - Range of fire scenarios, etc.

Regardless of the approach used the use of reliability in the analysis is similar. It alters the distribution of possible outcomes from the fire scenario(s) being considered. Where uncertainty is being explicitly considered in the analysis it is appropriate to identify the uncertainty in the reliability otherwise a deterministic measure (conservative, most-likely) may be used.

QRA approaches can be used to derive single risk measures for example the annualised risk of loss of life for an individual or an average societal risk, or they can produce risk curves. Where uncertainty is introduced these become distributions of individual risk and families of societal risk curves.

QRA can be distilled down to design values. For example for certain building types the results of QRA can be reduced to correlations between critical variables such as fire growth rate, compartment height, etc., thus allowing rapid comparison of risks without detailed QRA. If this approach is used any consideration of reliability would be inherent in the correlated values unless reliability of systems is itself separated out as critical variable. The latter approach would make any assumptions about system reliability transparent.

8

Establishing Fire Protection Systems Effectiveness

Introduction

Effectiveness of the fire protection system is the product of its efficacy and its reliability.

In an absolute approach the effectiveness needs to exceed some benchmark value. This is not generally possible in isolation since the benchmark of interest is the overall life safety performance for which the fire protection system is only one component. Some measures do exist for fire protection system (or sub system) performance which may provide some guidance for effectiveness.

The analysis undertaken to assess fire protection system effectiveness is necessarily (relatively) simplistic. Typically only a subset of all potential fire scenarios are considered. The fire protection system operation is approximated using correlations or computer models. Effectiveness is generally assumed be a characteristic of the whole system.

The effectiveness of a proposed system can be compared with a benchmark design but as with the absolute approach the measure of interest is the overall level of risk. If the only significant variable between the two designs is the fire protection system and it can be demonstrated that the effectiveness of the system is equal or better than the benchmark design then this may be an acceptable approach. In order for this approach to be practical a set of benchmark designs would need to be established with derived risk levels expressed in terms of individual and societal risk. If such a set of designs could be established it would provide a practical alternative to full QRA when considering system design alternatives.

Reliability assessment for a given design would be based upon an established value or distribution adjusted by factors according to the design, installation, maintenance and environment for the system.

Efficacy assessment for systems would be based upon deviation from accepted Standards. For simplicity it is assumed that systems compliment with Standards have 100% efficacy for design fire scenarios[14]. Efficacy will therefore only be reduced as a result of systems not being Standards compliment (which may be due to design, installation or maintenance issues), or from the system being exposed to a fire scenario outside of the range of design fires for the system, or from partial failures of the system which result in reduced efficacy.

Candidate System Designs

The design of systems varies and this variation will have an effect on system reliability.

Sprinkler Systems

For sprinkler systems there are two basic design types for light hazard occupancies:

Residential sprinkler systems. These use specially designed sprinklers which are tested for a residential design fire scenario with monitoring of tenability. The design basis and per sprinkler water consumption means that these systems can operate with significantly lower water demands than conventional systems. As with any system or component tested in this way there is always the risk of ‘design to pass the test’. Concerns that this was happening and the shrinking margin of safety resulted in a minimum water flow being required from the sprinklers regardless of test performance.

Light hazard system. In New Zealand light hazard systems consist of 10mm sprinklers with the design allowing for six sprinkler head operation with a minimum flow per sprinkler. Use of quick response sprinklers is required where these are used in sleeping areas or areas serving sleeping areas.

It is not apparent from the system design basis which system would offer greater efficacy in situations where either is allowed (namely residential occupancies). Some of the incident data sources are based upon residential systems but it is not apparent what the design basis is. If it is NFPA13D then this would allow comparison with the residential design criteria.

There are key aspects of sprinkler system design which can vary from design to design and which might be expected to have a significant impact on reliability and efficacy.

Design option	**Impact on Reliability**
Water supply arrangements	
Single supply, dual supply	Single supply less reliable – no redundancy
Towns main – dead end feed, multiple feed	Dead end feed less reliable – single point of failure
Boosted towns main	Reliability determined by towns main reliability, efficacy function of pump for many systems
Tank and pump	Reliability dependent on pump reliability
Bypass valveset	Increased reliability (availability)
Monitored isolation valves	Increased reliability

Table 8.1: Relation between design option for sprinklers and reliability

Although brigade connection does not appear on all systems it would be expected to be present on any system installed or altered under the current Standard and non brigade connected systems are not considered as an alternative design approach.

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[14] In reality this value would not be 100% as there is a (relatively) small probability that a fully operational, standards compliant system, exposed to a design fire which it is meant to control would not be able to control the fire. This small likelihood has not been separately identified but is integrated into the reliability value used to determine the overall system effectiveness.

Alarm Systems

Variation in alarm system design is predominantly in the type of detector used and the choice between analogue addressable systems and conventional systems. Whilst experimental work exists which has examined detector performance no research has been found quantifying the impact of other design choices on system reliability or efficacy.

Design option	**Impact on Reliability**
Detector Type	Different reliability/efficacy for different types
Analogue or conventional	Analogue systems have more intelligent monitoring but are more complex.
Wiring	Redundancy of class B type wiring
Alerting	Higher efficacy for voice based evacuation systems
Evacuation method	Impacts on number of people exposed to fire and stage of fire when people move within the building. Considered a system design variable as is dependent on system design for this feature to be available.

Table 8.2: Relation between design option for alarm systems and reliability

Stairwell Pressurisation System

Design option	**Impact on Reliability**
Fan Type	Fixed fan and variable speed fan have different failure modes.
Detection system	Detection system choice (normally smoke detection) will itself impact on overall reliability of system
Sprinkler protection	Presence of sprinkler system alters the expected design fire for which the SPS will need to control smoke
Design basis	Various specific aspects of the design including the construction, fire/smoke separation, environmental variables, will all impact on overall reliability of the system

Table 8.3: Relation between design option for stairwell pressurisation systems and reliability

Design Freedom

Variation in design is caused by a number of drivers:

- Cost of system
- Architectural requirements
- Trade-offs in design
- False alarm performance
- Maintainability

Some design approaches increased the reliability of systems by either improving safety margin in design performance or by creating a more robust system, these include:

- Basing hydraulic performance on worst case
- Considering impact of detector impairment on system performance
- Use of multiple systems (defence in depth)
- Use of conservative parameters for calculating the required safe egress time (RSET)

Critical System Components

These are components or subsystems which if failure occurs could credibly[15] lead to complete system failure or significant loss of efficacy.

Sprinkler System

Following table lists critical sprinkler system components, the likely failure modes and underlying risk factors. Quality of testing and maintenance is a risk factor for all failure modes and is not explicitly listed.

Component/Sub-system	Failure Mode(s)	Risk factor(s)
Sprinkler head	Cracked bulb	Mechanical damage, temperature cycling, installation.
	Bulb plastered over	Installation.
	Cap stuck	System age.
	Sprinkler blocked	Commissioning (flushing of pipe-work), strainer on water supply, water quality, corrosion.
	Missing deflector	Mechanical damage, installation.
Connecting pipe work	Joint failure	Thin wall pipe, corrosion, installation, pressure testing.
	Pipe failure (below ground)	Corrosion, pressure testing, support, ground movement.
	Pipe failure (above ground)	Thin wall pipe, corrosion, pipe supports, pressure testing, mechanical damage.
Alarm valve	Doesn’t open	Installation.
Isolation valves	In wrong position (open when should be closed, or vice versa)	Locking and monitoring of valves, security of valve house, training, labelling of valves.
	Failed closed (e.g. dropped gate valve)	Training
Water supply		
Pump (electric)	Does not start	Power off, dropped phase, pressure switch failure, controller failure.
Pump (diesel)	Does not start	No starting power, fuel supply, pressure switch failure, controller failure.
Pump	No or inadequate flow	Pump installed backwards, blockage to discharge, impellor damage, pump underspeed, change in suction conditions.
Towns main	No or inadequate flow	Blockage in pipe work, closed or part closed street valve
Tank	Catastrophic tank failure	Installation, ground movement
Tank	No or inadequate flow	Pump filling, monitoring, vortex plate blockage, detached tank liner
Alarm signalling	No signal generated	Alarm valve failure, SGD failure, and communication failure.

Table 8.4: Sprinkler System Critical Components and Subsystems

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[15] Relatively minor issues such as gauge shading, detectors spacing out of rule, etc., would not be expected (in itself) to lead to system failure. There is a risk associated with such deficiencies but it is not practical to quantify this risk and it is considered to be small compared with the risk presented by critical component failure. The impact of these minor issues is accounted for to some extent by associating a higher level of risk with systems which are less well maintained.

Alarm System

The following table lists critical alarm system components, the likely failure modes and underlying risk factors. Quality of testing and maintenance is a risk factor for all failure modes and is not explicitly listed.

Component/Sub-system	Failure Mode(s)	Risk factor(s)
Detector	Detector disconnected	Education, correct detector selection, analogue addressable detectors.
	Detector covered over	Education, correct detector selection.
	Detector blocked/dirty	Analogue addressable detectors
	Incorrect installation	Installation, analogue addressable, commissioning
	Detector isolated	Training, analogue addressable, commissioning
Connecting wiring	Wiring fault	Installation, protection from mechanical damage, protection from fire damage.
Fire Alarm panel	Panel isolated	Training, analogue addressable, commissioning, security
	Panel communication fault	Installation, commissioning
Power Supply	Loss of power	Installation, commissioning, security
Alarm signalling	No signal generated	Alarm valve failure, SGD failure, and communication failure.

Table 8.5: Alarm System Critical Components and Subsystems

Stairwell Pressurisation System

The following table lists critical stairwell pressurisation system components, the likely failure modes and underlying risk factors. Quality of testing and maintenance is a risk factor for all failure modes and is not explicitly listed.

Component/Sub-system	Failure Mode(s)	Risk factor(s)
Fan	Disconnected Connected Backwards	Training, Commissioning
Damper	Incorrect Installation	Training, Commissioning
Door Closure	Incorrect Installation	Training, Commissioning
Detector	Detector disconnected	Education, correct detector selection, analogue addressable detectors.
	Detector covered over	Education, correct detector selection.
	Detector blocked/dirty	Analogue addressable detectors
	Incorrect installation	Installation, analogue addressable, commissioning
	Detector isolated	Training, analogue addressable, commissioning
Connecting wiring	Wiring fault	Installation, protection from mechanical damage, protection from fire damage.
Control Panel Failure	Hardware Failure Software Failure Comms Failure	Training, Commissioning
Fire Alarm panel	Panel isolated	Training, analogue addressable, commissioning, security
	Panel communication fault	Installation, commissioning
Power Supply	Loss of power	Installation, commissioning, security
Alarm signalling	No signal generated	Alarm valve failure, SGD failure, communication failure.

Table 8.6: Stairwell Pressurisation System Critical Components and Subsystems

Impact of Installation and Commissioning Quality

System Installation Quality for Fire Alarms

Some attempts have been made to quantify the impact of quality of installation and commissioning on the reliability of systems. Lees has data on the human error which can be used as a basis for determining whether faults will occur. This common approach has been used by Moore and Tims, and by Zhao and is the basis for the initial tables presented. Using this data gives the following subjective assessment of fault probability.

Installation Quality	Probability of an Installation Fault
High	0.01
Medium	0.16
Low	0.3

Table 8.7: Alarm Installation Quality and Probability of an Installation Fault

After installation probability of a fault may increase markedly due to a number of causes notably:

Post Installation Fault Issues	Where Observed
Alterations to layout leaving areas without detection	Office and retail occupancies
Programming alterations to panels	Analogue addressable panels
Tampering with smoke detectors	Apartments

Table 8.8: Post Installation Fault Issues for Alarms

The commissioning process is generally considered to be more robust and indicative probabilities for failure to find a fault in a system (based on Zhao, and Moore and Tims).

Commissioning Quality	Probability of the Commissioning Failing to identify an Installation Fault
High	0.003
Medium	0.01
Low	0.1

Table 8.9: Alarm Commissioning Quality and Probability of failing to find an Installation Fault

Combining the installation and commissioning processes gives the following range of likelihood of faults post installation and commissioning.

Commissioning Quality	Installation Quality		
	Low	Medium	High
High	0.0009	0.0005	0.00003
Medium	0.003	0.0016	0.0001
Low	0.03	0.016	0.001

Table 8.10: Alarm Fault Probability Matrix for Range of Installation and Commissioning Quality

Industry survey information indicates fault levels on alarm systems as installed in NZ are at the mid range of this scale where systems installed and commissioned may have an installation fault level of around 1 in 1000. Based upon this an indicative scale appropriate for New Zealand may be:

Installation and Commissioning Quality	Probability of Fault Post Commissioning
High	0.0001
Medium (Typical)	0.001
Low	0.03

Table 8.11: Alarm Fault Probability for Combined Installation and Commissioning Quality

System Installation Quality for Fire Sprinkler Systems

The level of control for sprinkler systems is considered higher with greater emphasis on 3rd party inspection and commissioning. Based upon this it is proposed that the fault probability post installation and commissioning is lower for sprinkler systems than it is for fire alarm systems. Noting that this probability reflects significant faults that would prevent system acceptance. It is likely there will be minor items that are either accepted during commissioning or that will be dealt with during the maintenance period for the system. A relatively high value has been left for the case where installation and commissioning are of a relatively low standard.

Installation and Commissioning Quality	Probability of Fault Post Commissioning
High	0.00001
Medium (Typical)	0.0001
Low	0.01

Table 8.12: Sprinkler Commissioning Quality and Probability of failing to find an Installation Fault

As for alarm systems there are changes post commissioning which impact on the fault levels observed in the systems.

Post Installation Fault Issues	Where Observed
Alterations to layout leaving areas without sprinklers	Office and retail occupancies
Changes in towns main water supplies (pressure reduction)	All occupancies
Occupancy changes (increasing fire-load)	Office and retail occupancies
Sprinkler obstruction from storage/furnishings	All occupancies

Table 8.13: Post Installation Fault Issues for Sprinklers

System Installation Quality for Stairwell Pressurisation Systems

Given the dependency of these systems on the detection system for effective operation the baseline fault probability can be taken from the fire alarm system (table reproduced below).

Installation and Commissioning Quality	Probability of Fault Post Commissioning
High	0.0001
Medium (Typical)	0.001
Low	0.03

Table 8.14: Stairwell Pressurisation System Commissioning Quality and Probability of failing to find an Installation Fault

Further to this the complications added by the fans, dampers and construction increase the likelihood of faults. Compared to sprinkler systems in New Zealand, stairwell pressurisation systems do not have a well defined design approval and inspection process. Commissioning requirements should be addressed against the installation standard (typically AS 1668.1) but (anecdotally) the quality of commissioning is variable.

Fazio(2007) and others have commented on the high likelihood that stairwell pressurisation systems will not be operational as designed following installation or even initial commissioning. Based upon these comments the fault probabilities seem optimistic and the following are proposed as indicative fault levels. This is discussed further in the section on on-demand reliability for stairwell pressurisation systems.

Installation and Commissioning Quality	Probability of Fault Post Commissioning
High	0.01
Medium (Typical)	0.1
Low	0.3

Table 8.15: Stairwell Pressurisation System Fault Probability for Combined Installation and Commissioning Quality

Component/Sub-System Reliability

Power supply

The critical power supply for fire protection systems generally consists of two components, the mains power supply and a battery backup supply. For some systems there may be an emergency power supply available in addition to the mains power and battery backup.

Mains power

The reliability concern with mains power supply is not of a failure on demand as much as the risk of a fire being coincident with a loss of power, faults on mains supply are unlikely to remain undetected in residential and commercial buildings for periods that are significant compared with the maintenance period duration. Steciak gave mains power failure rate for a specific location as 4.75E-6 per hour. Table 8.16 below summarises the resulting fault probabilities and unavailability [proportion of time system would not be available] (based on equations 1 and 2) for a range of assumed maintenance periods and fault repair times. For comparison the fault probability used for a risk analysis of a specific building is included.

Maintenance Period	4 weeks	3 months	1 year	NA
Fault Probability	0.0032	0.01	0.041	0.00005[16]
Unavailability [1 hour Repair Time]	3.6E-7	1.2E-6	4.6E-6	5.6E-9
Unavailability [8 hour Repair Time]	**2.9E-6**	9.4E-6	3.7E-5	4.5E-8
Unavailability [24 hour Repair Time]	8.7E-6	2.8E-5	1.1E-4	1.3E-7
Unavailability [1 week Repair Time]	6.1E-5	2.0E-4	7.8E-4	9.5E-7

Table 8.16: Mains power unavailability

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[16] The 140 Williams Street project used a fault probability of 0.00005 which is significantly lower indicating that when specific power supply arrangements are considered with stable supplies and redundancy the values may be substantially lower than the estimates given by Steciak.

The most likely (but expected to be somewhat conservative) maintenance period and repair time combination is proposed to be a 4 week maintenance period and an 8 hour repair time. The upper credible bound is estimated to be an unavailability of 1E-4, the lower credible bound 5E-8, and the most likely value 3E-6. Proposed distribution type triangular or PERT.

Battery Backup

The main concern is that failure of the battery backup could go undetected for the maintenance period. If a 4 week maintenance period is assumed then based on the battery reliability value reported in Lees of 3E-6/hr the failure probability is 0.002. For poorly maintained systems where the effective maintenance period may be 3 months or 1 year would result in failure probabilities of 0.006 and 0.026 respectively. Proposed distribution type triangular or PERT with likely value 0.002, upper bound 0.026 lower bound taken as 50% of likely value, 0.001.

Diesel Generator

If present then the risk that the generator will be in fault and this will not be detected over the maintenance period. Lees gives failure rate for diesel generator of 3E-4/hr. Based on a monthly maintenance period the failure probability is 0.2 with longer effective maintenance periods (3 monthly) this failure probability increases to 0.48. These values are high and would be expected to be unrealistic for situations where the generator is a critical facility for other purposes, for example where it is providing backup power for a hospital and generator failure could cause catastrophic results. In these situations the generator may have a reliability more in line with a well maintained diesel fire pump of 2E-6/hr. The on demand failure probability based on power station data reported in Lees was 0.005.

The resulting failure probability based on a monthly maintenance period is 0.0015. Proposed distribution type triangular or PERT with likely value 0.2, upper bound 0.48 lower bound taken as 0.0015. This distribution is very broad and should be adjusted to accommodate the likely maintenance conditions for the generator.

Smoke Detector Failure

Various failure rate data is available for smoke detectors these are summarised below:

Detector type	**Failure Rate [hr-1]**	**Source**
Smoke	1.2E-6	Steciak and Zalosh
Smoke (Ionisation)	3.4E-9[17]	Gupta
Smoke (Ionisation)	1.6E-6 (lower) 4.6E-6 (mean) 7.6E-6 (upper)	OREDA
Smoke (Photoelectric)	2.1E-6 (mean)	OREDA

Table 8.17: Smoke Detector Failure Rates

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[17] For hospital environments, value for critical failure, across all fault modes including false alarm figure rises to 1E-7

The resulting failure probabilities for selected failure rates for a range of maintenance periods is presented below. Additionally the unavailability is presented for selected cases.

Failure Rate [hr-1]	**Failure Probability for various Maintenance Periods**				**Unavailability**[18]
	4 weeks	**3 months**	**12 months**	**5 years**	
(Steciak) 1.2E-6	0.0008	0.0026	0.010	0.051	1.4E-4
(Gupta) 3.4E-9	2.3E-6	7.4E-6	3.0E-5	0.00015	4.1E-7
(OREDA) 7.6E-6	0.0051	0.016	0.064	0.28	7.7E-4

Table 8.18: Smoke Detector Failure Probabilities

The critical maintenance period for smoke detectors under NZS 4512 is 5 years. This is the period for testing of detector function[19]. All more frequent testing is at the panel and although some fault conditions may be detected at the panel this will be limited. Based on a 5 year maintenance cycle the failure probabilities predicted by Steciak and OREDA appear very high. For a medium sized commercial building of 10 floors with 30 smoke detectors per floor the OREDA data would imply that during the maintenance cycle 84 detectors would need replacing because of failure. This is not the experience in the field. There are some reasons which may be surmised for the higher failure rates proposed by OREDA. These are detectors in the offshore environment which is by its nature more challenging than normal environments particularly in terms of potential for corrosion. The Gupta value is explicitly for 'fatal' fault conditions, i.e. those which prevent the detector from functioning in a fire situation; other values are given for non-fatal faults and for nuisance alarms, this explicit distinction is not made with the Steciak and OREDA values. If the Steciak failure rate is adjusted based upon the proportion of fatal faults in the Gupta analysis (i.e. it is assumed the ratio of fatal faults to non fatal faults is assumed constant) then the resulting failure probability for a 5 year maintenance cycle reduces from 0.051 to 0.0017.

Reports of detector failure by contractors in New Zealand are relatively low for normal occupancies (as opposed to challenging environments) of the order of 1 in 5000 detectors or less. This would give a probability of 0.0002 (or less) of detector failure. This value is consistent with the value predicted using the Gupta failure rate value and a 5 year maintenance cycle.

Failure rates for smoke detection from the Peacock et al are of the order of 5E-4 per demand.

The value given by Gupta is for ionisation smoke detection. It is assumed that the failure rate for photoelectric smoke detectors would be similar. The OREDA data gives failure rates for photoelectric detectors as around 2/3rd the value of ionisation detectors and based upon this the assumption that the results from Gupta can be applied to photoelectric smoke detectors appears reasonable.

Failure of a single detector may not be critical for system efficacy providing other detectors exist in the smoke-cell then the fire will be detected albeit delayed. For stairwell pressurisations it is likely that this delay would not be significant and these systems are less sensitive to failure due to a single detector failure. Once multiple detectors are required to fail the probability reduces considerably. For example for the stairwell pressurisation system the acceptance criteria may be that any detector within the smallest smoke cell operates. This may be an apartment for example with 3 detectors. The probability of failure then reduces from 0.00015 to $(0.00015)^3 = 3.4\text{E-}12$ (assuming the fault is independent). Given the reliability of other stairwell pressurisation components the detector fault reliability is unlikely to be a significant contributor to the overall

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[18] Based on 4 week maintenance period and 24 hour repair time. OREDA data gives mean repair time as 4.5 hours but in practice time to respond and replace could easily exceed this time and 24 hours seems a more reasonable estimate.

[19] The testing is actually a rolling test undertaken annually with a 5 year cycle. Assuming a 5 year maintenance period leads to some conservatism in the predicted failure probability.

reliability of the system.

Based on the above analysis it is proposed that the likely failure probability for smoke detection (ionisation or photoelectric) is taken as 0.00015 and the corresponding likely system unavailability (due to detector fault repair) taken as 4.1E-6. There is little evidence to base the bounds upon. In the absence of better information the value based on the adjusted (fatal faults) Steciak rate could be selected giving an upper bound 0.0017 and an arbitrary lower bound of 50% of the likely value = 0.000075. In terms of detector failure rates this equates to a range of approximately 1 in 500 detectors to 1 in 14,000 detectors. An asymmetric triangular or PERT distribution is suggested.

Heat Detector Failure Rates

Various failure rate data is available from OREDA data for heat detectors. The mean failure rate is 2.3E-6/hr. Peacock et al indicate heat detector failure rates of 3E-4 per demand.

Maintenance periods of interest are the same as for smoke detectors

Failure Rate [hr-1]	Failure Probability for various Maintenance Periods				Unavailability[20]
	4 weeks	3 months	12 months	5 years	
(OREDA) 2.3E-6	0.0017	0.0050	0.020	0.095	4.6E-6

Table 8.19: Heat Detector Failure Rate

Based on the above analysis it is proposed that the likely failure probability for heat detection is taken as 0.0017 and the upper bound taken as 3E-4 and lower bound taken as 0.005. An asymmetric triangular or PERT distribution is suggested.

Sprinkler Head Failure

Limited failure rate data is available for sprinklers. The Nash and Young data presented is a combination of failures to active, unwanted activation and non fatal faults (leaks, etc). Information on sprinkler failure to operate was based upon testing of sprinklers at the laboratory rather than in-situ results. Probability of complete blockage was reported as 0.009 for new sprinklers and 0.017 for old sprinklers however given the nature of the study it is questionable whether this value could be treated as indicative of the population of sprinklers of interest.

Sprinkler Type	Failure Probability (on demand)	Source
Old Sprinkler	0.017	Nash & Young
New Sprinkler	0.009	Nash & Young
Sprinkler	<1E-6	Grosse et al

Table 8.20: Sprinkler Head on Demand Failure Rate

Values for overall operational reliability for sprinkler systems include 98.9% (Watanabe) and 98.1% (Thomas et al) based upon NFPA data sprinkler head failure would account for at most 5% of those cases where the system was not operationally reliable. From this it is suggested sprinkler head failure is approximately 5.5E-4 to 9.5E-4 (or less) with an average of 7.5E-4.

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[20] Based on 1 month maintenance period and 24 hour repair time. OREDA data gives mean repair time as 8.5 hours but in practice time to respond and replace could easily exceed this time and 24 hours seems a more reasonable estimate.

It is proposed that the failure probability for sprinklers is taken as 7.5E-4 which is considered conservative for new systems. The upper bound will be based on the Nash and Young testing (0.009) and the lower bound taken as 1E-6. For old systems it is possible that this distribution would not be conservative. Observed failure probabilities of sprinklers in systems 50 or more years old can be at least as high as the rates quoted by Nash and Young. It should be noted that NZS 4541 has introduced a requirement for testing and (if necessary) replacement of sprinklers once they reach certain ages as summarised in table 8.21:

Sprinkler Type	**Testing Frequency**
Solder type with temperature rating greater than 168C.	5 years
Quick response sprinklers	20 years
All other sprinklers	50 years

Table 8.21: Sprinkler Head Testing Frequency

The lifetime of sprinklers (and other items such as some detectors) can be modelled using an exponential distribution. The probability of detector failure for detectors of age of T^* is related to the exponential function distribution parameter λ by the expression:

$$P(T > T^*) = \lambda \int_{T^*}^{\infty} e^{-\lambda t} dt \Rightarrow \left. e^{-\lambda t} \right|_{\infty}^{T^*} \Rightarrow e^{-\lambda T^*}$$

If λ is known the probability of failure can be calculated. λ can be obtained from failure data. As a crude approximation it can be evaluated from a point value of failure rate for a sample of known age. With the introduction of the requirement for testing into the New Zealand Standard this data will become more commonly available and better assessment of the failure rate of sprinkler heads of certain types under certain conditions will be able to be made. This can then be used to provide more precise information on failure probabilities over the planned life of a building.

As well as on demand failure there is another failure rate associated with sprinklers and that is failure due to damage to the defector or the bulb. The result of this is non operation or compromised operation. In office and apartment occupancies the occurrence of these faults is relatively rare. More common are issues of paint on bulbs due to poor masking but this cannot be readily converted into failure rates.

Fire Alarm Panel Failure

Fire alarm panel rates are taken from a number of sources ranging from the offshore industry data of OREDA through to the hospital study of Gupta. OREDA data showing higher failure rates than other sources.

Failure	**Failure Rate [hr-1]**	**Source**
Fire panel failure	1.5E-5 4.8E-5 [mean] 8.4E-5	OREDA
Fire panel failure	6.8E-6	Gupta
Fire panel failure	8.5E-6	SSL Study

Table 8.22: Fire Alarm Panel Failure Rates

Critical maintenance periods for fire alarm panels are monthly and 12 monthly. The 12 monthly test includes functional checks on communication to and from the panel to ancillary devices.

Failure Rate [hr-1]	Failure Probability for various Maintenance Periods		Unavailability[21]
	Monthly	12 months	
4.8E-5	0.034	0.34	9.4E-5
6.8E-6	0.0049	0.057	1.3E-5
8.5E-6	0.0062	0.071	1.7E-5

Table 8.23: Fire Alarm Panel Hardware Failure Rates

The survey data from Fazio indicates an expected value for fire panel faults of 0.035 (SD 0.049) or excluding extreme data 0.024 (SD 0.033). These correspond to the higher end of the range of values derived here.

The failure probabilities are greater than the 0.001 probability used in the 140 William Street project. Industry experience here indicates panel (hardware) faults are relatively rare with new systems but partial isolations, etc, may account for a probability of 0.005. For this reason the value of 0.0049 will be suggested as the most likely value with an upper bound of 0.034 and a lower bound of 0.001. The higher failure probabilities will also account to some extent for those failure modes associated with communication to ancillary devices that would not be identified in the monthly tests.

The survey data from Fazio indicates an expected value for fire panel reprogramming of 0.11 (SD 0.15) or excluding extreme data 0.043 (SD 0.045). The risk of this is dependent on the complexity of the system and the need for system programming changes.

Software Faults

For the fire alarm panel it is assumed there is activity on the panel once per year on average. Assuming that the probability of introducing an error during work on the system is given by:

Work Quality	Probability of an Introduced Fault
High	0.01
Medium	0.16
Low	0.3

Table 8.24: Fire Alarm Panel Software Indicative Probability of an Introduced Fault

These equate to the following failure rates:

Work Quality	Failure Rate [hr-1]
High	1.1E-6
Medium	1.8E-5
Low	3.4E-5

Table 8.25: Fire Alarm Panel Software Failure Rates

It is possible that these introduced errors would be picked up at monthly checks, quarterly testing or annual testing. The resulting failure probabilities for each maintenance period is summarised below.

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[21] Based on 1 month maintenance period and 24 hour repair time.

Failure Rate [hr-1]	Failure Probability for various Maintenance Periods		
	Monthly	3 monthly	12 monthly
1.1E-6	8.00E-04	2.40E-03	9.60E-03
1.8E-5	1.30E-02	0.038	0.14
3.4E-5	2.40E-02	0.071	0.26

Table 8.26: Fire Alarm Panel Software Failure Rates

For a simple panel if low inspection quality is assumed for both the monthly testing, and quarterly testing (Failure probability 0.1) then the average failure probability can be calculated.

Failure Rate [hr-1]	Mean Failure Probability
7.5E-8	1.0E-3
1.2E-6	1.6E-2
2.3E-6	3.0E-2

Table 8.27: Mean Fire Alarm Panel Software Failure Rates for Simple Panel

The expected value would be towards the high end of this range. Proposed distribution is expected value 1E-3, upper bound 3E-2 and upper bound 5E-4.

For a more complicated panel the detection of faults will be assumed to be unlikely at the monthly test (10% probability), possible at the quarterly checks (50%). It is assumed the fault is found at the annual inspection.

Failure Rate [hr-1]	Mean Failure Probability
7.5E-8	5.5E-3
1.2E-6	8.1E-2
2.3E-6	1.5E-1

Table 8.28: Mean Fire Alarm Panel Software Failure Rates for Complex Panel

For conservatism the expected value is taken at the middle of this range. Proposed distribution is expected value 8.1E-2, upper bound 1.5E-1 and upper bound 5.5E-3.

These values are consistent with industry estimates (survey industry) which estimate panel software rates of approximately 1 in 10 for pre-commissioned new or altered systems.

Diesel Fire Pump

Diesel fire pump failure rates are given below from OREDA data and Rönty et al.

Failure	Failure Rate [hr-1]	Source
Diesel Pump Failure	1.2E-4 2.1E-4 [mean] 3.1E-4	OREDA
Diesel Pump Failure	1.0E-6 1.7E-6 [mean] 2.6E-6	Rönty et al

Table 8.29: Diesel Pump Failure Rates

Typical maintenance periods on diesel pumps are at 1 month, 3 months and 12 months intervals. For these maintenance periods the corresponding failure probabilities are given in table 8.30:

Failure Rate [hr-1]	Failure Probability for various Maintenance Periods			Unavailability[22]
	1 month	3 month	12 months	
2.1E-4	0.14	0.37	0.84	1.5E-3
1.7E-6	0.0012	0.0037	0.015	1.3E-5
1.0E-6	0.0007	0.0022	0.009	8.0E-6

Table 8.30: Diesel Pump Failure Probabilities

Not including the extremely high vales derived from the OREDA failure rate data with extended maintenance periods the failure probabilities equate to a range between 86% through 99.63% up to 99.93%. These values are consistent with on demand data from OREDA, data from Lees, and estimates from Feeney, the comparison between estimates summarised in table 8.31.

Case	Lower	Likely	Upper
Proposed	86%	99.63%	99.93%
OREDA	87%	99.33%	99.96%
Lees	97%	98.6%	99.5%
Feeney	88%	-	99.85%

Table 8.31: Comparison between Diesel Pump Failure Probabilities

Based on this an asymmetric triangular or PERT distribution with likely value of failure probability of 0.0037 and bounds of 0.14 and 0.0007 is proposed.

Electric Fire Pump

Electric fire pump failure rates are from OREDA and Rönty et al.

Failure	Failure Rate [hr-1]	Source
Electric Pump Failure	2.4E-5 7.2E-5 [mean] 1.7E-4	OREDA
Electric Pump Failure	2.8E-7 7.1E-7 [mean] 1.5E-6	Rönty et al

Table 8.32: Electric Pump Failure Rates

Typical maintenance periods on electric pumps are at 1 month, 3 months and 12 months intervals. For these maintenance periods the corresponding failure probabilities are given in table 8.33:

Failure Rate [hr-1]	Failure Probability for various Maintenance Periods			Unavailability[23]
	1 month	3 month	12 months	
7.2E-5	0.05	0.14	0.47	8.4E-4
7.1E-7	0.0005	0.0015	0.0062	8.5E-6
2.8E-7	0.0002	0.0006	0.0024	3.3E-6

Table 8.33: Electric Pump Failure Probabilities

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[22] Based on monthly maintenance period and 96 hour repair time. OREDA data gives mean repair time as 88 hours which has been rounded up to 4 days.

[23] Based on monthly maintenance period and 144 hour repair time. OREDA data gives mean repair time as 130 hours which has been rounded up to 6 days.

Not including the extremely high values derived from the OREDA failure rate data with extended maintenance periods, the failure probabilities equate to a range between 95% through 99.85% up to 99.98%. These values are consistent with on demand data from OREDA as shown in table 8.34.

Case	Lower	Likely	Upper
Proposed	95%	99.85%	99.98%
OREDA	97.9%	99.33%	99.88%

Table 8.34: Comparison between Electric Pump Failure Probabilities

Based on this an asymmetric triangular or PERT distribution with likely value of failure probability of 0.0015 and bounds of 0.05 and 0.0002 is proposed.

Towns Main

Town main supply failure on demand relates primarily to unavailability due to planned or unplanned work on the supply.

Various estimates are available for town main failure rates. Data presented is from Auckland and Wellington.

Year	Auckland		Wellington	
	Break/km per Year	Unavailability Probability/km	Break/km per Year	Unavailability Probability/km
2006	0.30	1.7E-4	0.33	3.0E-4
2005	0.29	1.6E-4	0.31	2.8E-4
2004	0.37	2.1E-4	-	-
Average	0.32	1.8E-4	0.32	2.9E-4

Table 8.35: Indicative Town Main Unavailability Rates per km for Auckland and Wellington

The distance of interest is a failure in that portion of the pipe supplying the sprinkler system. Separation distances between isolation values would not be expected to exceed 500m in central city locations. Providing that supply can be independently fed from two directions then the length of interest is 0.5km. If the failure is a valve failure this distance needs to double to allow for isolation of two sections of the main. In other areas isolation valve spacings could extend significantly beyond 500m or it may not be possible to feed from two directions. For the sake of argument a value 10 times the Auckland CBD value has been taken as the length of interest. The lower bound on unavailability has been set at 50% of the expected value.

Case	Auckland CBD	Wellington CBD	Out of CBD
Expected	9E-5	1.5E-4	9E-4
Valve Failure	1.8E-4	2.9E-4	1.8E-3
Lower bound	4.5E-5	7.2E-5	4.5E-4

Table 8.36: Indicative Town Main Unavailability Rates for Exposed Sprinkler System in Auckland and Wellington and nominal Out of CBD Location

These values are consistent with the values referenced by Feeney and Zalosh and lower than the values referenced by Rönty et al.

Case	Unavailability
Proposed	9E-5 (Auckland) 1.5E-4 (Wellington) 9E-4 (Provincial)
Feeney	7E-5 (Auckland) 6E-5 (Melbourne)
Zalosh	3.6E-4 (US)
Rönty et al	2.6E-4 to 2.5E-3 (Finland)

Table 8.37: Comparison of Unavailability Values

It is proposed to use the following values for the generic case. An expected value of 9E-5 a lower bound of 4.5E-5 and an upper bound of 4.5E-4. This would be non conservative for situations with low levels of redundancy in the supply.

The risk of partially impaired supply is significantly higher with industry opinion ranging from 0.015 to 0.001. The risk of reduction in town main pressure is higher still with opinion that this is causing non-compliance in between 0.1 and 0.01 of systems.

Tank

HSE (Safety Report Assessment Guide: Highly flammable liquids) reports 3E-6/yr for risk of catastrophic failure. Rönty et al report maximum of 6.5E-3/yr for tank failure but this value was extrapolated based upon lack of events. Lees references 1.6E-5/yr and 3E-5/yr for catastrophic storage tank failure. The average of the Lees value is taken as the likely case. The HSE value as the lower bound and twice the higher Lees estimate as the upper bound.

Based on these and assuming a 6 week reinstatement time the corresponding unavailability is summarised below.

Case	Failure Probability	Unavailability
Likely	2.3E-5	2.6E-6
Lower Bound	3E-6	3.5E-7
Upper Bound	6E-5	6.9E-6

Table 8.38: Tank Failure Probabilities and Unavailability

Isolation of Water Supply

The risk of isolation of supply is primarily from isolation of the town main. Under NZS 4541 other isolation valves in the system (notably the main stop valve) are required to be monitored. The risk is most likely due to human error but could also be due to failure of the valve in the closed position. Valve closure is well represented as an error condition under NFPA statistics (being the single largest failure mode) but this is not reflected in NZ statistics.

Industry estimates are that isolation failure probability (on demand) is less than 0.0001. Rates are higher for systems without monitoring perhaps reaching as high as 0.0033. It is strongly dependent on the quality of testing and maintenance since detection of the situation is most likely as a result of the drain test and street valve inspection test which is carried out 3 monthly. An upper limit of 0.00001 has been selected which would assume low failure rates.

The risk of monitoring failure can be high (some indicated 0.066). If the observed rate for unmonitored systems is multiplied by the probability of monitoring failure the resulting probability is 0.0002. Risk of failure due to mechanical failure of the valve is estimated as 0.00003 based upon NFPA Statistics where isolation valve failure is cited as the cause.

For the main stop valve it is assumed there is activity on the stop valve once per year on average. Assuming that the probability of introducing an error during work on the system is given by:

Work Quality	**Probability of an Introduced Fault**
High	0.01
Medium	0.16
Low	0.3

Table 8.39: Nominal Probability of Introduced Fault (Isolation of Supply)

Estimates of monitoring failure could be as high as 0.066. It is assumed for simplicity that if monitoring is functioning correctly the fault will be quickly remedied and the risk can be neglected.

The effective failure rates are given by the annualised failure rate for introduced fault multiplied by the probability that the fault will not be automatically detected by monitoring systems:

Work Quality	**Failure Rate [hr-1]**
High	7.5E-8
Medium	1.2E-6
Low	2.3E-6

Table 8.40: Failure Rates for Isolation of Supply

It is possible that this would be picked up at monthly checks, quarterly testing or annual testing. The resulting failure probabilities for each maintenance period is summarised below.

Failure Rate [hr-1]	**Failure Probability for various Maintenance Periods**		
	Monthly	**3 monthly**	**12 monthly**
7.5E-8	5.4E-5	0.00016	0.00065
1.2E-6	8.7E-4	0.0026	0.010
2.3E-6	1.7E-3	0.0050	0.020

Table 8.41: Failure Probability (Accidental Valve Isolation) for Various Testing Intervals

If low inspection quality is assumed for the monthly testing (Failure probability 0.1), and typical inspection quality for the quarterly testing (failure probability 0.01) then the average failure probability can be calculated.

Failure Rate [hr-1]	**Mean Failure Probability**
7.5E-8	6.51E-5
1.2E-6	1.05E-3
2.3E-6	2.05E-3

Table 8.42: Mean Failure Probability (Accidental Valve Isolation)

The expected value would be at the upper end of this range. The proposed distribution is expected value 6.5E-5, upper bound 2E-3 lower bound 3.2E-5. Asymmetric PERT or triangular.

For an unmonitored valve two cases will be considered. A potential for introducing a fault annually (appropriate for waterway equipment) and 4 yearly (appropriate for isolation valves from tank supplies).

Work Quality	Failure Rate [hr-1]	
	Annual	**4 Yearly**
High	1.1E-6	2.5E-7
Medium	1.8E-5	4.5E-6
Low	3.4E-5	8.5E-6

Table 8.43: Failure Rates for Introduced Errors for Unmonitored Valves

Critical inspection/maintenance frequencies are monthly, 3 monthly and 12 monthly.

Failure Rate [hr-1]	Failure Probability for various Maintenance Periods					
	Yearly (Waterway equipment)			**4 Yearly (Tank Supply)**		
	Monthly	**3 monthly**	**12 monthly**	**Monthly**	**3 monthly**	**12 monthly**
1.1E-6/2.5E-7	8.00E-03	2.40E-03	9.60E-03	1.80E-04	5.40E-04	2.20E-03
1.8E-5/4.5E-6	1.30E-02	0.038	0.14	0.0037	0.0098	0.038
3.4E-5/8.5E-6	2.40E-02	0.071	0.26	0.0062	0.018	0.071

Table 8.44: Failure Probabilities for Various Maintenance Periods for Yearly and 4 Yearly Potential for Introduction of Inadvertent Valve Closure

For each case if low inspection quality is assumed for the monthly testing (Failure probability 0.1), and typical inspection quality for the quarterly testing (failure probability 0.01) then the average failure probability can be calculated.

Failure Rate [hr-1]	Mean Failure Probability	
	Yearly (Waterway equipment)	**4 Yearly (Tank Supply)**
7.5E-8	7.45E-03	2.18E-04
1.2E-6	1.56E-02	4.34E-03
2.3E-6	2.89E-02	7.43E-03

Table 8.45: Mean Failure Probabilities for Various Maintenance Periods for Yearly and 4 Yearly Potential for Introduction of Inadvertent Valve Closure

The expected value would be at the upper end of this range. The proposed distributions are for waterway equipment expected value 7.5E-3, upper bound 2.9E-2 lower bound 3.7E-3. For tank supply expected value 2.2E-4, upper bound 7.4E-3 lower bound 1.1E-4 Asymmetric PERT or triangular.

There is also potential for isolation of floor valves. These are monitored but there have been reported instances of this monitoring being disabled to allow alteration work to be undertaken on the floor. Industry estimates of the frequency of this vary widely from 1 in 10,000 to 1 in150 (system basis), on a floor basis if a 10 storey building average is assumed then this ranges from 1 in 100,000 to 1 in 1,500. The risk is primarily with office buildings where tenancy fit-outs are common and the probabilities for these would be higher. The derived main stop valve failure probabilities provide a subjective basis for a failure distribution.

Failure Rate [hr-1]	Mean Failure Probability
7.5E-9	6.51E-6
1.2E-7	1.05E-4
2.3E-7	2.05E-4

Table 8.46: Mean Failure Probability for Floor Valve Isolation

Expected value 6.5E-5, upper bound 2E-3 lower bound 3.2E-5. Asymmetric PERT or triangular.

A simple approach to account for number of floors is to divide failure probability by number of floors but this will over estimate risk for low rise buildings and underestimate it for high rise buildings. If an average number of floors is assumed for buildings with floor isolation valves of 10 floors (minimum mandated number of floors for fitting of isolation valves is 6). Then this can be used to derive an approximate per floor failure probability.

Expected value 6.5E-6, upper bound 2E-4 lower bound 3.2E-6. Asymmetric PERT or triangular.

This would be expected to be lower still for buildings with infrequent alteration work. Subjectively by an order of magnitude giving a resultant per floor failure probability.

Expected value 6.5E-7, upper bound 2E-5 lower bound 3.2E-7. Asymmetric PERT or triangular.

For buildings with frequent alteration work the expected value could approach the upper bound, i.e. the per floor probability of failure could approach 2E-4.

Alarm Valve Failure

Critical alarm valve failure data is available from a number of sources including OREDA data as well as a number of researchers into fire protection system reliability.

Failure	**Failure Rate [hr-1]**	**Source**
Alarm Valve (deluge) Failure	2.8E-6 5.8E-6 [mean] 9.4E-6	OREDA
Alarm Valve Failure	7.4E-8 1.4E-7 [mean] 2.3E-7	Rönty et al
Alarm Valve Failure	4.6E-9	Nash and Young

Table 8.47: Alarm Valve Failure Rates

Maintenance on the alarm valve is limited to exercising the valve through the drain test (quarterly) and overhaul of the valve 4-yearly.

Failure Rate [hr-1]	**Failure Probability for various Maintenance Periods**		**Unavailability**[24]
	3 month	**4 yearly**	
5.8E-6	0.012	0.18	1.1E-5
1.4E-7	0.0003	0.005	2.8E-7
7.4E-8	0.00016	0.0026	1.5E-7
4.6E-9	1E-5	0.00016	9.2E-9

Table 8.48: Alarm Valve Failure Probabilities

Not including the high value derived from the OREDA failure rate data with extended maintenance periods the failure probabilities equate to a range between 98.8% through 99.63% up to 99.999%. These values are consistent with on demand data from OREDA for deluge valves which given the complexity of deluge valves would be expected to be significantly less reliable than standard wet pipe sprinkler alarm valves.

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[24] Based on quarterly maintenance period and 8 hour repair time.

Case	Lower	Likely	Upper
Proposed	98.8%	99.98%	99.999%
OREDA (Deluge)	94.8%	99.0%	>99.9%

Table 8.49: Comparison of Reliability Values with OREDA Data

It is proposed to use the following values for the generic case. OREDA data has been excluded as it is considered overly conservative being based on offshore deluge valve performance. An expected value of 0.00016 a lower bound of 1E-5 and an upper bound of 0.005.

Pipe Array

The risk of failure on demand from the pipe work in the system is primarily due to pipe work being blocked. Indicative frequency of this occurring based upon NFPA data is 0.0018. Risk of this depends on quality of workmanship (removal of cut-outs), quality of commissioning including pipe flushing and the use of strainers on water supplies. A lower failure rate is considered appropriate for the following reasons:

- Lower water flow rates with high rise office/sleeping type occupancies reduces risk of debris in the pipe.
- Installation methods make inclusion of welding debris, etc, in the pipe unlikely.
- New Zealand’s relatively robust inspection and commissioning process.

Based upon this the following distribution is proposed. An expected value of 1.8E-4 a lower bound of 1E-5 and an upper bound of 1E-3.

Pipe systems may also fail due to leaks requiring the system to be repaired. Data from Rönty et al indicates mean pipe failure rate [hr-1]of 3.8E-10 per metre of pipe. For a typical 15,000m^2 office building distribution pipe work may account for approximately 6,000m of pipe work. Giving the indicative risk for a system of 2.2E-6 [hr-1]. The pipe work is only surveyed every two years and based on this frequency the failure probability is 0.038. Assuming the repair work can be undertaken within 24 hours of detection this equates to a system unavailability of 1E-4.

Stairwell Pressurisation Fan

Fan Hardware Failure

Fans come in various arrangements depending on the design requirement. Trend is towards using axial fans with variable speed drives. Failure rate data for fans from a number of sources is given below.

Failure	Failure Rate [hr-1]	Source
Axial Fan	8.2E-6	Hobson and Stewart
Centrifugal Fan	7.8E-5	Hobson and Stewart
Fan	4.5E-5	Klote
Fan	1.9E-4	Moore and Tims
Fan	5.7E-5	Lees
Fan	2.4E-5 4.8E-5	NCSR data
Fan	1.8E-5 2.6E-5 3.5E-5	OREDA

Table 8.50: Fan Hardware Failure Rates

Critical fan maintenance period is 3 monthly when there would be expected to be a functional test on the fan. One year has been included as the timeframe for major maintenance.

Case	**Failure Rate [hr-1]**	**Failure Probability for various Maintenance Periods**		**Unavailability**[25]
		3 month	**1 year**	
Hobson and Stewart - Axial Fan	8.2E-6	0.018	0.069	9.7E-5
- Centrifugal Fan	7.8E-5	0.16	0.49	8.6E-4
Klote	4.5E-5	0.094	0.32	5.1E-4
Moore and Tims	1.9E-4	0.34	0.81	1.9E-3
Lees	5.7E-5	0.12	0.39	6.4E-4
NCSR data	2.4E-5	0.051	0.19	2.8E-4
	4.8E-5	0.099	0.34	5.4E-4
OREDA	1.8E-5	0.038	0.15	2.1E-4
	2.6E-5 [mean]	0.055	0.20	3.0E-4
	3.5E-5	0.073	0.26	4.0E-4

Table 8.51: Fan Hardware Failure Probability

For modern installations utilising axial fans the failure probability would be expected to be at the lower end of this range (i.e. towards 0.018). This is supported by the survey by Fazio which gave hardware failure probabilities in the range 0.012 to 0.046, the mean value being 0.029. This value is consistent with the lower range NCSR and OREDA data and will be taken as the likely value. The lower range will be taken as 0.012 and the upper range as 0.12. Although this is lower than the value predicted by the Moore and Tims failure rate data it should be noted that the on demand failure probability used by Moore and Tims was 0.119 as they assumed a higher frequency of maintenance. The proposed distribution form is asymmetric triangular or PERT.

Whether the distribution is appropriate depends on the situation. It is expected to be appropriate for axial fans with or without variable speed drive arrangements. If centrifugal fans are used or there are other factors which would impact on reliability (notably the maintenance arrangements) then the distribution used should be amended accordingly.

Fan System Isolated

There is a risk of isolation due to human error or fault condition. Fault condition includes loss of communication between the mechanical services board and the fire control panel.

Human error includes[26]:

- Isolation of the SPF at the MSSB
- Isolation of the SPF at the fire alarm panel
- Key isolation at the SPF installation

The probability of introducing an error during work on the system is given by:

Work Quality	**Probability of an Introduced Fault**
High	0.01
Medium	0.16
Low	0.3

Table 8.52: Introduced Fault Probability (Fan System Isolation)

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[25] Based on quarterly maintenance period and 48 hour repair time.

[26] Additionally systems may be isolated to allow testing, maintenance or alterations.

It would be expected that, in general, work would be occurring at the higher quality end of the range given the relative simplicity of the task, the inherent safeguards against unwanted isolation of systems (indication, labelling, and test procedures).

Based upon assumed quarterly activity rate of maintenance then the following table summarises the derived failure probabilities. For simplicity it is assumed that all introduced faults are detected at the next maintenance period.

Case	**Failure Rate [hr-1]**	**Failure Probability for various Maintenance Periods**	
		1 month	**3 months**
High Quality	4.6E-6	0.003	0.01
Medium Quality	7.3E-5	0.052	0.15
Low Quality	1.4E-4	0.10	0.26

Table 8.53: Fan System Isolation Failure Probability

The values derived from the survey by Fazio are typically of the order of 0.01 if extreme survey results are ignored or in the range 0.033 to 0.049 if they are included. The former is consistent with low error rate introduction within a quarterly cycle which is the expected case for stairwell pressurisation systems. The higher value is due to a single much higher estimate from the survey and there is a high level of uncertainty associated with the result. An error at the fire alarm panel has a lower failure probability indicated by the survey. The value is 0.004 which is consistent with an infrequent error introduced during a monthly maintenance cycle which is the situation for work on the fire alarm panel.

For the specific error conditions the following table gives the statistics for the cases. The bracketed values are where outlying survey results have been eliminated.

Fault Condition	**Mean**	**Standard Deviation**
Isolation of the SPF at the MSSB	0.033 (0.01)	0.04 (0.006)
Isolation of the SPF at the fire alarm panel	0.0033	0.005
Key isolation at the SPF installation	0.048 (0.0067)	0.11 (0.010)

Table 8.54: Summary Survey Results for Isolation Causes

Based upon the above the following distributions are proposed. Where it is non negative the lower bound has been taken as one standard deviation below the mean. If this is not possible it has been taken as 50% of the mean. The upper bound has been taken as two standard deviations from the mean. This represents a conservative distribution assuming the mean reflects the true reliability. For highly complex systems the potential for errors may be higher.

Fault Condition	**Likely value**	**Lower bound**	**Upper Bound**
Isolation of the SPF at the MSSB	0.010	0.004	0.018
Isolation of the SPF at the fire alarm panel	0.0033	0.0016	0.013
Key isolation at the SPF installation	0.0067	0.0033	0.027

Table 8.55: Proposed Reliability Ranges for Fan Isolation Fault Conditions

VSD Faults

Hardware faults

Hardware faults on the variable speed drive are separated out into wiring faults and relay faults. From Fazio (amended by local survey responses) the estimates of the mean and standard deviation are summarised in table 8.56. The bracketed values exclude the outlying data points.

Fault Condition	**Mean**	**Standard Deviation**
Wiring Faults	0.034 (0.023)	0.050 (0.034)
Relay Faults	0.010 (0.001)	0.030 (0.003)

Table 8.56: Summary Survey Results for VSD Hardware Faults

These values are consistent with the installation fault levels based upon good installation practice (0.01 risk of introduction of faults, with derived failure rate of 3E-6/hr). With a 6 month maintenance cycle this yields a failure probability of 0.013 and with a 12 month maintenance period a failure probability of 0.026.

The following distributions for failure probability are proposed (upper bound is 2 Standard deviations above the mean, lower bound based on credible minimum failure rates).

Fault Condition	**Expected value**	**Lower bound**	**Upper bound**	**Distribution**
Wiring Faults	0.034	0.01	0.134	PERT or Triangular
Relay Faults	0.010	0.001	0.070	

Table 8.57: Proposed Failure Rates for VSD Hardware Faults

VSD Microprocessor Fault

Microprocessor faults on the VSD are divided into algorithm faults and microprocessor (physical) faults. From Fazio (amended by local survey responses) the estimates of the mean and standard deviation are summarised in table 8.56. The bracketed values exclude the outlying data points.

Fault Condition	**Mean**	**Standard Deviation**
Algorithm Fault	0.094 (0.06)	0.10 (0.056)
Microprocessor Fault	0.024 (0.021)	0.017 (0.015)

Table 8.58: Summary Survey Results for VSD Microprocessor Faults

The following distributions for failure probability are proposed (upper bound is 2 Standard deviations above the mean, lower bound based on credible minimum failure rates). Software fault data for computers (Lees) indicates typical failure rate of 0.002 which is an order of magnitude lower than the expected value proposed.

Fault Condition	**Expected value**	**Lower bound**	**Upper bound**	**Distribution**
Algorithm Fault	0.094	0.01	0.20	PERT or Triangular
Microprocessor Fault	0.024	0.001	0.058	

Table 8.59: Proposed Failure Rates for VSD Microprocessor Faults

Pressure Sensor Fault

Pressure sensor faults are divided into two groups. Firstly a generic hardware fault and secondly a performance fault whereby the sensor does not perform as per the design. Both fault types have been considered as critical which is expected to be conservative since there may be failure modes which still result in effective performance of the stairwell pressurisation system. From Fazio (amended by local survey responses) the estimates of the mean and standard deviation are summarised in table 8.60. The bracketed values exclude the outlying data points.

Fault Condition	**Mean**	**Standard Deviation**
Sensor cannot meet design requirement	0.095 (0.028)	0.16 (0.021)
Hardware fault	0.050	0.036

Table 8.60: Summary Survey Results for Pressure Sensor Faults

The following distributions for failure probability are proposed. For performance failure (not meeting design) mean has been taken from trimmed survey data as small number of high fault estimates from the survey distorted the data. The interpretation is that these represent pre-commissioning status and these higher fault rates may be appropriate if modelling failure rates for systems where it is known that commissioning and/or maintenance are poor. The lower bound has been taken as 50% of this mean value and the upper bound taken as one standard deviation above the mean based upon the untrimmed data. For general hardware fault upper bound is 1 Standard deviation above the mean, lower bound lower bound selected to be the same as for sensor not meeting design requirement.

Fault Condition	**Expected value**	**Lower bound**	**Upper bound**	**Distribution**
Sensor cannot meet design requirement	0.028	0.014	0.11	PERT or Triangular
Hardware fault	0.050	0.014	0.086	

Table 8.61: Proposed Failure Rates for Pressure Sensor Faults

Damper Failure

Dampers may be motorised or barometric.

Dampers may fail for a number of reasons depending on the type. They may fail open (or too open) or closed (or too closed). The former causing too much pressure relief and hence risk that smoke will enter stairwell, the latter that door opening forces will be excessive.

Hardware failure incorporates dampers jamming or sticking or not having full movement. Failure due to incorrect weight adjustment (barometric dampers) or wiring faults (motorised damper) or motor torque problems (motorised damper) are considered separately.

Damper Hardware Failure

This failure mode covers the damper jamming, being blocked, actuator failure, etc. Data is available from a number of sources including process industries data from OREDA and Lees as well as data from fire system researchers including Fazio. Failure rates from the literature are summarised in table 8.62.

Failure	Failure Rate [hr-1]	Source
Damper	3E-3	Steciak
Damper	6.6E-3	Lees
Damper	2.3E-6 6.6E-7 1.4E-7	Rowekamp et al.
Damper and Actuators (Motorised Damper)	7.3E-7 8E-6 1.6E-5	OREDA

Table 8.62: Failure Rates for Dampers

Critical maintenance periods for dampers are 6 monthly and annually. It is possible in principle that fault conditions could be detected more frequently than this but this could not be relied upon. Table 8.63 summarises the failure probabilities based upon these maintenance frequencies.

Case	Failure Rate [hr-1]	Failure Probability for various Maintenance Periods		Unavailability[27]
		6 months	1 year	
Steciak	3E-3	0.99	0.99	>2.7E-3
Lees	6.6E-3	>0.99	>0.99	>2.7E-3
Rowekamp et al.	2.3E-6 6.6E-7 1.4E-7	0.010 0.0029 0.0006	0.020 0.0057 0.0012	2.7E-5 7.9E-6 1.7E-6
OREDA	7.3E-7 8E-6 1.6E-5	0.0032 0.034 0.067	0.0063 0.067 0.13	8.7E-6 9.4E-5 1.8E-4

Table 8.63: Failure Probabilities for Dampers

There is wide divergence in the values. The high failure rates predicted using the values for failure rate from Steciak and Lees are not observed in the field. The values from Rowekamp et al are based upon fire damper data but are in a highly controlled environment (nuclear power industry) and would be expected to represent the upper range of damper reliability. Survey results from Fazio indicate damper failure rates of 0.133 for dampers jamming (barometric type) and 0.079 for (mechanical) failures of motorised dampers.

Damper Type	Mean	Standard Deviation
Barometric	0.133	0.053
Motorised Damper	0.079	0.064

Table 8.64: Summary Survey Results for Damper Hardware Faults

For barometric style dampers the standard deviation for the survey data is 0.053. The upper bound will be taken as two standard deviations from the mean = 0.24. This value is higher than any of the surveyed values. The lower bound will be taken as the mean value from the OREDA data = 0.034. If a normal distribution is assumed then the probability that any given value is greater than the lower bound [P(X>0.034)] is 97% and the probability that any given value is less that the upper bound [P(X<0.24)] is 98%.

For motorised dampers the standard deviation for the survey data is 0.064. The upper bound will be taken as two standard deviations from the mean = 0.21. This value is higher than any of the

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[27] Based on quarterly maintenance period and 48 hour repair time.

surveyed values. The lower bound will be taken as the mean value from the OREDA data =0.034. If a normal distribution is assumed then the probability that any given value is greater than the lower bound [P(X>0.034)] is 70% (i.e. relatively conservative lower bound) and the probability that any given value is less that the upper bound P(X<0.21) is 98%. Distributions in each case will be asymmetric PERT distributions.

Damper Type	Expected value	Lower bound	Upper bound	Distribution
Barometric	0.133	0.034	0.24	PERT or Triangular
Motorised	0.079	0.034	0.21	

Table 8.65: Proposed Failure Probability Distribution for Dampers

Damper Weights

For barometric dampers weight adjustment may be an issue which can lead to failure. From the survey by Fazio (including additional NZ survey results) the mean value was 0.13 with a standard deviation of 0.051. In the absence of information to set specific bounds it is proposed that a truncated (at 0 and 1) normal distribution be used (0.13, 0.051).

Fault Condition	Expected value	Standard Deviation	Distribution
Damper Weight Adjustment	0.13	0.051	Truncated Normal

Table 8.66: Proposed Failure Probability Distribution for Damper Weight Faults

Insufficient Torque on Motor

The survey statistics from Fazio (including additional NZ survey results) gave a mean value of 0.017 and a standard deviation of 0.022. In the absence of information to set specific bounds it is proposed that a truncated (at 0 and 1) normal distribution be used (0.017, 0.022).

Fault Condition	Mean	Standard Deviation	Distribution
Insufficient Torque on Motor	0.017	0.022	Truncated Normal

Table 8.66: Proposed Failure Probability Distribution for Inadequate Damper Motor Torque

Wiring Faults

For motorised dampers wiring faults (for example reverse wiring) could cause system failure. Moore and Tims used a fault rate of 3E-6/hr. Based on a 6 monthly check on dampers this would result in a failure rate of 0.013, for an annual maintenance period (reflecting lower levels of maintenance) the probability increases to 0.026.

The likelihood of a wiring fault occurring during installation is a function of the quality of installation and the commissioning process. The matrix presented earlier (reproduced here for convenience) related the commissioning quality and installation quality to the generic failure probability from faults introduced through installation and not detected at commissioning.

Commissioning Quality	Installation Quality		
	Low	Medium	High
High	0.0009	0.0005	0.00003
Medium	0.003	0.0016	0.0001
Low	0.03	0.016	0.001

Table 8.67: Matrix Relating Installation and Commissioning Quality to Failure Probability

Fazio used a value of 0.1 for damper wiring faults based upon a single survey response. This is higher than would be expected even allowing for low installation quality and low commissioning quality. It is however credible for non commissioned systems with medium to low installation quality. New Zealand survey respondents gave lower values including zero faults though it was commented that there is wiring faults may be picked up during the commissioning process. The value from Fazio also appears high given there is separate identification of faults relating to actuator/motor failure.

The probability estimates of 3 damper wiring related faults is summarised below based on combined data from Fazio and New Zealand survey sources:

Failure	Mean	Standard Deviation
Reversed wiring	0.069 (0.018)	0.14 (0.019)
Wrong fuses	0.015 (0.01)	0.017 (0.01)
Fuses incorrectly installed.	0.013 (0.0067)	0.018 (0.0082)

Table 8.68: Summary Survey Results for Damper Wiring Faults

It is proposed to use a truncated (0 and 1) normal distribution (based on the trimmed survey results) for each of these faults.

Failure	Mean	Standard Deviation	Distribution
Reversed wiring	0.018	0.019	Truncated Normal
Wrong fuses	0.010	0.010	
Fuses incorrectly installed.	0.0067	0.0082	

Table 8.69: Failure Probability Distributions for Damper Wiring Faults

To cover the possibility for other wiring faults associated with the system a general fault probability is introduced. Based upon good installation practice and a 6 monthly maintenance cycle this yields an expected failure probability of 0.013. The lower bound being arbitrarily taken as 50% of this value and the upper bound as 200% of this value.

Failure	Expected value	Lower bound	Upper bound	Distribution
General Wiring Fault	0.013	0.006	0.026	PERT or Triangular

Table 8.70: Failure Probability Distributions for Damper Wiring Faults

Controller Error

There is potential for controller error. Failure rates will be based upon alarm panel controller rates and for reference failure rates for electronic circuit boards have been included.

Failure	Failure Rate [hr-1]	Source
Circuit (electronic)	1E-7	Rasmussen
alarm panel failure	6.8E-6	Gupta
alarm panel failure	8.5E-6	Moore and Tims
PLC failure	1.1E-6	Lees

Table 8.71: Failure Rates for Electronic Panels and Circuits

Critical maintenance periods for dampers and associated controllers are 6 monthly and 12 monthly. Based upon these maintenance periods the associated failure probabilities are given in Table 8.72.

Failure Rate [hr-1]	Failure Probability for various Maintenance Periods	
	6 months	12 months
1E-7	0.00044	0.00087
6.8E-6	0.029	0.058
8.5E-6	0.036	0.072
1.1E-6	0.0050	0.0096

Table 8.72: Failure Probabilities for Controllers

The expected value will be taken as 0.029 (Gupta), the lower bound as 0.00044 and the upper bound as 0.05. Distribution is taken as asymmetric PERT or triangular.

Failure	Expected value	Lower bound	Upper bound	Distribution
Controller Fault	0.029	0.00044	0.050	PERT or Triangular

Table 8.73: Failure Probabilities Distribution for Controllers

Doors and Leakage

In the Fazio survey, questions were included regarding faults observed with doors. It is assumed the results presented by Fazio were on a per system basis, i.e. a report door fault frequency of 0.10 indicates that in 10% of installations surveyed there was a problem detected with one or more doors in the stairwell. An optimistic view (giving an upper limit) would be that only one door would be faulty, the pessimistic view would be that all doors would be faulty. The observation from New Zealand surveyed respondents was that for a properly commissioned system design issues around door performance were rare. The main observation being the potential for closer hardware to drift out of calibration with time. Locked doors were noted as an issue for testing and survey purposes where the stairwell door was also a secure door for a tenancy or apartment. This fault condition does not equate to an inherent loss in efficacy merely that the system cannot be said to comply with AS 1668.1. Doors damaged was not reported as a common issue from the New Zealand correspondents in contrast to the results from Fazio.

The bracketed values indicate an estimate of per door failure rates based on a 10 door stairwell and therefore can be seen as an indicative lower bound.

Failure	Mean	Standard Deviation
Door fits poorly	0.068 (0.0068)	0.077
Door hardware faulty	0.13 (0.013)	0.084
Door damaged	0.22 (0.022)	0.11
Door locked	0.11 (0.011)	0.076

Table 8.74: Summary Survey Results for Door Faults

The door damaged value and door locked value are based on extremely limited survey responses and these have a high degree of associated uncertainty. Since these responses were added in and were not in response to a preset question it is unclear what impact the damaged door would have on the system efficacy. As a worst case scenario this could result in a door jamming to the extent where it would prevent entry to the stairwell.

Table 8.75 summarises the probability failure distributions for door faults.

Fault Condition	Expected value	Lower bound	Upper bound	Distribution
Door fits poorly	0.072	0.0072	0.15	PERT or Triangular
Door hardware faulty	0.13	0.013	0.21	
Door damaged	0.22	0.022	0.33	
Door locked	*0.11*	*0.040*	*0.19*	

Table 8.75: Failure Probability Distributions for Door Faults

Air Movement Factors

There are a number of fault conditions which are external to the system but could impact on the system efficacy. These have been classified as air movement factors since they all impact on the control of air movement in the stairwell either allowing too much air flow out of the stairwell or not enough. The former will result in under pressurisation and hence may result in smoke movement into the stairwell, the latter would result in over pressurisation and hence the potential for high door opening forces. These have been grouped into four separate categories based upon the work of Fazio. The survey results are summarised in Table 8.76.

Failure	Mean	Standard Deviation
Blocked relief	0.20	0.16
Holes introduced	0.077 (0.054)	0.071 (0.050)
Too Tight	0.095	0.069
Too Loose	0.034 (0.023)	0.035 (0.022)

Table 8.76: Summary Survey Results for Air Movement Faults

The definitions of each of these is somewhat arbitrary. It is not clear whether the fault reported would lead to significant issues in terms of loss of efficacy. New Zealand respondents reported that blocked relief (or inadequate relief) was the most significant of these issues.

Based upon the survey results the proposed distributions are to use the survey mean data and standard deviations in truncated (0 and 1) normal distributions.

Failure	Mean	Standard Deviation	Distribution
Blocked relief	0.20	0.16	Truncated Normal
Holes introduced	0.077	0.071	
Too Tight	0.095	0.069	
Too Loose	0.034	0.035	

Table 8.77: Failure Probability Distributions for Air Movement Faults

Overall SPF Performance

Fazio also indicated an overall probability of the fan being poorly designed or installed. This was based upon a single survey result and comments provided with the value indicate that the 0.75 value was associated with a range of design and installation issues and the value is proposed to be a reflection of the respondent's view of the overall reliability of systems (at least pre-commissioning). For this reason this value will not be used in the fault tree presented as an overarching failure value.

New Zealand correspondents report that approximately 60% to 70% of stairwell pressurisation systems are independently commissioned. Further the view is that significant design issues exist in approximately 50% of system pre-commissioning. This 50% figure being comparable to the 75% figure reported by (the single survey response) Fazio, the difference perhaps being due to installation faults. Of the systems independently commissioned we might expect between a 0.1

and 0.01 rate of failure to detect a fault by competent IQPs. This would give a post commissioning fault rate between 0.5% and 5% for independently commissioned systems. For systems not independently commissioned the quality of the commissioning process would be expected to be lower maybe of the order of between 0.1 and 0.3 probability of failure to identify and rectify faults. This would give a post commissioning fault rate of between 5% and 15% for non independently commissioned systems.

There faults are due to system design and configuration, it does not include installation faults. These would account for a further percentage of faults maybe increasing the number of systems with post commissioning faults up to 10% to 30% of systems.

Summary of Component and Subsystem Reliabilities

Unless noted otherwise failure type is undetected failure during maintenance cycle. Isolation failures are due to human error or equipment failure. The values do not include planned isolations which are considered separately.

Ranges broad to cover possible variations in installation and maintenance quality. If the uncertainty in these can be reduced this can be reflected in the distribution.

Component/subsystem	**Expected Value**	**Upper Bound**	**Lower Bound**	**Distribution**	**Comment**
Mains Power	3E-6	1E-4	5E-8	PERT/Triangular	Failure and resulting unavailability of supply
Battery Backup	2E-3	2.6E-2	1E-3	PERT/Triangular	
Diesel Generator	0.2	0.48	1.5E-3	PERT/Triangular	Expected value conservative for well maintained generator
Smoke Detector	1.5E-4	1.7E-3	7.5E-5	PERT/Triangular	
Heat Detector (poor performance)	1.7E-3	5E-3	3E-4	PERT/Triangular	Conservative values appropriate for old heat detectors and challenging environments.
Heat Detector (expected performance)	3E-4	1.7E-3	1.5E-4	PERT/Triangular	
Sprinkler Head	7.5E-4	1E-6	9E-3	PERT/Triangular	Failure on demand. Expected value conservative for new sprinkler systems.
Fire Alarm Panel - Hardware	4.9E-3	0.034	1E-3	PERT/Triangular	
Fire Alarm Panel – Software (Simple System)	1E-3	3E-2	5E-4	PERT/Triangular	Subjective, based upon human error rates. Values consistent with failure data for industrial computers.
Fire Alarm Panel – Software (Complex System)	0.081	0.15	0.0055	PERT/Triangular	Subjective, based upon human error rates. Expected to be conservative for all but the most complex systems. Consistent with surveyed fault rates on smoke management systems.
Fire Alarm System Wiring	0.013	0.026	0.006	PERT/Triangular	
Diesel Fire Pump	3.7E-3	0.14	7E-4	PERT/Triangular	Covers range of reliability to account for different levels of maintenance.
Electric Fire Pump	1.5E-3	5E-2	2E-4	PERT/Triangular	Covers range of reliability to account for different levels of maintenance.
Towns Main (Auckland)	9E-5	1.8E-4	4.5E-5	PERT/Triangular	Failure and resulting unavailability of supply. Not appropriate where it is credible loss of towns main supply could remain undetected for extended periods. Normal operating conditions only – no account taken of extreme events, i.e. earthquake.
Towns Main (Wellington)	1.5E-4	2.9E-4	7.2E-5	PERT/Triangular	
Towns Main (Outside CBD)	9E-4	1.8E-3	4.5E-4	PERT/Triangular	

Tank	2.6E-6	6.9E-6	3.5E-7	PERT/Triangular	Failure and resulting unavailability of supply until replaced/repaired. Normal operating conditions only – no account taken of extreme events, i..e earthquake.
Isolation of towns main	1E-4	3.3E-3	1E-5	PERT/Triangular	Subjective based on industry opinion and analysis of valve mechanical failure rates (critical failure). Lower bound value reflects infrequent maintenance (long detection times).
Isolation of main stop valve	6.5E-4	2E-3	3.2E-5	PERT/Triangular	Subjective based on industry opinion of monitoring not being present or not operating, and assumed human error rates. Lower failure rate than towns main would be expected because of monitoring.
Isolation of unmonitored isolation valve (off TM)	7.5E-3	2.9E-2	3.7E-3	PERT/Triangular	Subjective based on industry opinion of monitoring not being present or not operating, and assumed human error rates.
Isolation of unmonitored isolation valve (off tank supply)	2.2E-4	7.4E-3	1.1E-4	PERT/Triangular	Subjective based on industry opinion of monitoring not being present or not operating, and assumed human error rates.
Isolation of floor valve.	6.5E-4	2E-3	3.2E-5	PERT/Triangular	Subjective based on industry opinion of monitoring not being present or not operating, and assumed human error rates. Values are for system. Need to adjust for floor basis by dividing by number of floors. Simple division will over represent hazard for low rise buildings and under-represent for very high buildings. Hazard will also be higher for building where there is frequent tenancy fit-out work. Risk will be lower for buildings where fit out work is unusual.
Alarm Valve	1.6E-4	5E-3	1E-5	PERT/Triangular	
Pipe Array – demand failure	1.8E-4	1E-3	1E-5	PERT/Triangular	Values based upon NFPA data for pipe blockages. Strong function of quality of workmanship and commissioning. Assumed higher value for New Zealand given controls on installation and commissioning.
Pipe Array - unavailability	1.6E-8/metre	3.2E-8/metre	8.0E-7/metre	PERT/Triangular	Expected availability based upon two yearly survey. Other testing and maintenance activities would not be expected to reliably pick up issues with pipe work. Value represents an unavailability due to need to repair the pipe work from issues such as leaks. A distribution has been assumed based upon leaks being ±100% of the expected value. This is considered reasonable for office and apartment occupancy types. For situations where higher corrosion rates are possible the distribution should be adjusted.
Stairwell Pressurisation Fan – Fan Hardware Failure	0.029	0.12	0.012	PERT/Triangular	Failure due to mechanical damage, or associated equipment failure. This distribution is appropriate for typical maintenance arrangements for axial fans. If maintenance arrangements deviate from normal practice or centrifugal fans are used the distribution should be reviewed.
Stairwell Pressurisation Fan –					Failure due to isolation of the fan in error.

Fan Isolation					
a) At the MSSB	0.010	0.018	0.004	PERT/Triangular	
b) At the Fire Panel	0.0033	0.013	0.0016		
c) Key isolation	0.0067	0.027	0.0033		
Variable Speed Drive – Hardware Faults					
a) Wiring Faults	0.034	0.134	0.01	PERT/Triangular	
b) Relay Faults	0.010	0.070	0.001		
Variable Speed Drive – Microprocessor Faults					
a) Software	0.094	0.20	0.01	PERT/Triangular	
b) Hardware	0.024	0.058	0.001		
Pressure sensor – Microprocessor Faults					
a) Performance below Design requirements	0.036	0.11	0.020	PERT/Triangular	
b) Hardware fault	0.056	0.096	0.020		
Damper Failure – Hardware					
a) Barometric Damper	0.13	0.24	0.034	PERT/Triangular	
b) Motorised Damper	0.079	0.21	0.034		
Damper Weights not Adjusted (Barometric damper)	0.13	Standard Deviation 0.051		Normal Truncated at 0,1.	
Damper Failure – Wiring					
a) Reversed wiring	0.016	Standard Deviation 0.016		Normal Truncated at 0,1.	
b) Wrong fuses	0.010	Standard Deviation 0.010			
c) Fuses installed incorrectly	0.0075	Standard Deviation 0.0096			
Damper Failure – General Wiring Fault	0.013	0.026	0.006	PERT/Triangular	

Controller Error	0.029	0.05	0.00044	PERT/Triangular	Significant uncertainty associated with this value.
Motor failure – insufficient torque	0.024	Standard Deviation 0.024		Normal Truncated at 0,1.	
Stairwell Door Faults					
a) Door fits poorly	0.072	0.15	0.0072	PERT/Triangular	
b) Door hardware faulty	0.13	0.21	0.013		
c) Door damaged	0.22	0.33	0.022		
d) Door locked	0.20	0.40	0.020		
Air Movement Faults					
a) Blocked relief	0.22	Standard Deviation 0.16		Normal Truncated at 0,1.	
b) Holes introduced	0.082	Standard Deviation 0.074			
c) Too tight	0.11	Standard Deviation 0.065			
d) Too loose	0.034	Standard Deviation 0.042			

Table 8.78: Summary of Failure Probability Distributions

Effects of Installation, Commissioning and Maintenance

The presented reliability distributions assume typical levels of installation, commissioning, and maintenance for expected values, and depend on the case there may be implicit or explicit consideration of the quality in the setting of the bounds.

Where there is confidence that the quality of installation, commissioning and maintenance will differ significantly from that which is typical the distributions may need to be altered to reflect this.

Maintenance Frequency for component

For a number of components and subsystems there are maintenance frequencies prescribed under the standards for the systems. Applicable Standards are NZS 4541 for sprinkler systems, NZS 4512 for alarm systems, and AS 1668.1 and AS 1851 for stairwell pressurisation systems.

Component/subsystem	System	Nature of test	Frequency
Mains Power	Sprinkler	Check	Monthly[28]
Battery Backup	Sprinkler	Check battery acid, battery age	Monthly
Battery Backup	Sprinkler	Replace one of the two sets of batteries	2 yearly
Battery Backup	Alarm	Check voltages, function and condition.	Monthly
Battery Backup	Alarm	Check fault condition from battery disconnect	Annual
Smoke Detector	Alarm	Visual check on all devices	Annual
Smoke Detector	Alarm	Check function with test smoke (or acceptable alternative)	Annual[29]
Heat Detector	Alarm	Visual check on all devices	Annual
Heat Detector	Alarm	Check function with heat source	Annual[30]
Sprinkler Head	Sprinkler	Visual check	2 yearly
Sprinkler Head	Sprinkler	Test for function	Typical 20 years then every 10 years
Fire Alarm Panel	Alarm	Test system function of isolated panel. Evacuation devices are only tested from the panel.	Monthly
Fire Alarm Panel	Alarm	Testing of Fire Brigade Alarm Interfaces	Monthly

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[28] Where diesel pumps are installed these are tested weekly so it would be expected that in this case power failure to the system would be detected at the weekly pump test.

[29] Minimum of 20% of detectors to be tested such that all detectors are tested within a 5 year cycle, with a minimum of one detector from each zone at each test. Tested detectors should be recorded to ensure rotation of the detectors being tested, if this is not undertaken then there is a real risk of problems with detectors remote from the panel.

[30] Minimum of 2% of detectors to be tested such that all detectors are tested within a 5 year cycle, with a minimum of one detector from each zone at each test. Tested detectors should be recorded to ensure rotation of the detectors being tested, if this is not undertaken then there is a real risk of problems with detectors remote from the panel.

Fire Alarm Panel	Alarm	Test ancillary device control from the panel	Yearly[31]
Fire Alarm Panel	Sprinkler	Testing of Fire Brigade Alarm Interfaces	Monthly
Fire Alarm Panel	Sprinkler	Functional testing	2 yearly
Fire Alarm System Wiring	All	As for panel	As for panel
Fire Alarm System Wiring	Alarm	Test fault condition on break in detector circuit.	Annual
Fire Alarm System Wiring	Alarm	Test fault condition on absence of zone circuit board.	Annual
Fire Alarm System Wiring	Alarm	Visual check on system.	Annual
Diesel Fire Pump	Sprinkler	Run under load	Weekly
Diesel Fire Pump	Sprinkler	Physical check	Monthly
Diesel Fire Pump	Sprinkler	Drain test	Quarterly
Diesel Fire Pump	Sprinkler	Service	Yearly
Diesel Fire Pump	Sprinkler	Major Service run for 2 hours	2 yearly
Diesel Fire Pump	Sprinkler	Flow test	2 yearly
Electric Fire Pump	Sprinkler	Run under load	Monthly
Electric Fire Pump	Sprinkler	Drain test	Quarterly
Electric Fire Pump	Sprinkler	Flow test	2 yearly
Towns Main	Sprinkler	Drain test	Quarterly
Towns Main	Sprinkler	Flow test	2 yearly
Tank	Sprinkler	Level check	Monthly
Tank	Sprinkler	Inspection	4 yearly
Isolation of towns main	Sprinkler	Inspection and operation[32]	Quarterly
Isolation of towns main	Sprinkler	Operation[33]	2 yearly
Isolation of main stop valve	Sprinkler	Visual check	Monthly[34]
Isolation of main stop valve	Sprinkler	Valve overhaul	4 yearly
Isolation of unmonitored isolation valve (off TM)	Sprinkler	Visual check	Quarterly[35]
Isolation of unmonitored isolation valve (off TM)	Sprinkler	Functional test	Annual[36]
Isolation of unmonitored isolation valve (off tank supply)	Sprinkler	Visual check	Quarterly

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[31] There is anecdotal evidence that this is sometimes not being done (or maybe only partially done) because of concerns over impact of operation of these devices/systems on building users or on other systems.

[32] In practice inspection of these valves is problematic because they may be difficult to locate or in positions where it would be unsafe to inspect.

[33] For dual supplies requirement is to test each supply independently this may require shutting of street valves. This suffers from the same problems as inspection of these valves.

[34] Other isolation valves (subsidiary isolation valves) are checked quarterly.

[35] In principle this should happen quarterly but with backflow prevention for example it may not be possible if the valves are not accessible to the contractor.

[36] Functional test of backflow prevention required annually may or may not be undertaken by the sprinkler system contractor.

Isolation of floor valve.	Sprinkler	Visual check	Quarterly[37]
Isolation of floor valve.	Sprinkler	Visual check	2 yearly
Alarm Valve	Sprinkler	Functional check	Quarterly
Alarm Valve	Sprinkler	Valve overhaul	4 yearly
Pipe Array	Sprinkler	Visual check	2 yearly
Stairwell Pressurisation Fan – Fan Hardware Failure[38]	SPS	Visual check and check for excessive noise, etc.	Quarterly
Stairwell Pressurisation Fan – Fan Hardware Failure	SPS	Check lubrication, adjustment, corrosion and cables	Annual
Stairwell Pressurisation Fan – Fan Hardware Failure	SPS	Functional test	Annual
Stairwell Pressurisation Fan – Fan Isolation	SPS	Visual and run check[39]	Quarterly
Variable Speed Drive – Hardware Faults	SPS	Visual and run check	Quarterly
Variable Speed Drive – Hardware Faults	SPS	Functional test	Annual
Variable Speed Drive – Microprocessor Faults	SPS	Run check	Quarterly
Variable Speed Drive – Microprocessor Faults	SPS	Functional test	Annual
Pressure sensor – Microprocessor Faults	SPS	Functional test	Annual
Damper Failure – Hardware	SPS	Visual inspection and operation	Annual
Damper Weights not Adjusted (Barometric damper)	SPS	Visual inspection and operation	Annual
Damper Failure – Wiring	SPS	Visual inspection	Quarterly
Controller Error	SPS	Check and functional test	Annual
Motor failure – insufficient torque	SPS	Functional test	Annual
Stairwell Door Faults	SPS	Full simulation	Annual
Air Movement Faults	SPS	Full simulation	Annual

Table 8.79: Summary of Maintenance Requirements under New Zealand/Australian Standards

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[37] Valves and supervisory devices should be checked quarterly. Anecdotal evidence is that this is not occurring.

[38] Fan hardware used for day to day operation as well as fire service requires frequent (monthly) checking of condition. This section is based upon requirements for standalone exit pressurisation systems.

[39] Run checks would be expected to detect gross faults but would not be expected to detect fault conditions which impact on system efficacy.

Unavailability

Unavailability associated with equipment failure has been considered in the reliability of components and sub-systems. Fire protection systems may also be unavailable for a number of other reasons including.

- Periodic testing (including surveys)
- Preventative maintenance activities
- Fire system alterations and extensions (most commonly as a result of tenancy fit out activities).
- Building activities which require system isolation.
- Re-instatement following damage to the system[40]
- Re-instatement following fire

The first two of these are predictable in as much as the frequency and scope of work is prescribed in the relevant Standards.

Unavailability Due to Failure

If a failure occurs then there will be a period of time before the equipment can be repaired or replaced and the system recommissioned. This is the unavailability due to failure and was calculated as part of the on demand reliability for key components and sub systems.

Unavailability due to failures with specific equipment items are summarised below in Table 8.80.

Component/subsystem	Expected Value
Mains Power	3E-6
Smoke Detector(s)	4E-6
Heat Detector(s)	4E-6
Fire Alarm Panel	1.3E-5
Diesel Fire Pump	5E-5
Electric Fire Pump	2.5E-5
Alarm Valve	1.5E-7
Stairwell Pressurisation Fan	2E-4
Barometric Damper	4E-4
Motorised Damper	2E-4

Table 8.80: Unavailability of Key Components Due to Failure

Unavailability values due to failure are generally small in comparison to the failure probabilities themselves, this is a simple consequence of the fact that repair times are short compared with the potential latency period for faults.

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[40] Earthquakes have the potential to cause significant system damage and consequent loss of availability; however specific analysis of the impact of earthquakes on the reliability of fire protection systems is outside of the scope of this study.

Testing and Maintenance

Fire Sprinkler System

The following activities from NZS 4541 all require the system to be isolated such that if a fire occurred during these activities system failure is probable. Activities where there is isolation of subsidiary functions (for example signalling to fire brigade) have not been considered here.

Testing/Maintenance Item	Frequency	Duration	Unavailability [-]
Diesel service	Yearly	0.5 day	4.6E-4
Survey Remedial Items	4 yearly	1 day	4.6E-4
Valveset overhaul	4 yearly	0.5 day	1.1E-4
Tank cleaning	4 yearly	2 days	4.6E-4
Sprinkler testing	10 yearly	1 day	9.1E-5
Approximate total for towns main system			6.6E-4
Approximate total for tank and pump system			1.1E-3

Table 8.81: Sprinkler System Maintenance Activities with Significant Unavailability

Alarm Systems

The following are based upon requirements under NZS 4512. The durations are based upon industry estimates and are believed to be conservative for typical systems. For unusually complex systems these values may need to be adjusted to account for the longer durations particularly for the survey and remedial activities.

Testing/Maintenance Item	Frequency	Duration	Unavailability [-]
Panel Test	Monthly	0.5 hours	6.8E-4[41]
Functional Test	Annual	2 hours	2.3E-4
Survey remedial items	Annual	2 hours	2.3E-4

Table 8.82: Alarm System Maintenance Activities with Significant Unavailability

Stairwell Pressurisation Systems

AS 1851 has a series of checks on the system but does not require the system to be disabled during these checks. However an allowance has been made for isolation during testing and also maintenance downtime. 8 hours per year has been assumed to give an expected unavailability of 9.1E-4. Of course the system will be effectively unavailable during any testing and maintenance work on the detection system so the unavailability of 9.1E-4 is in addition to any detection system unavailability.

Alterations to System or building

Alterations to apartment buildings that would necessitate system isolation are not frequent. Alterations to office buildings is more common. If buildings have associated retail areas then alterations in the retail portion may require the isolation of the system. Table 8.83 shows the number of consents for alterations to office buildings (figures for whole of New Zealand).

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[41] System still functional during these tests just isolated from brigade.

Year	# Consents for Alteration Work
1991	1179
1992	1435
1993	1820
1994	2276
1995	2417
1996	2299
1997	2040
1998	1956
1999	2144
2000	2032
2001	2023
2002	2010
2003	1961
2004	2069
2005	2009
2006	2135
Mean (last 10 years)	2038
Standard Deviation	63

Table 8.83: Number of Building Consents for Office Buildings [Source: SNZ]

There is some uncertainty over interpretation of these figures for the following reasons:

1. It does not identify high rise buildings
2. Buildings may be unoccupied
3. Alterations may not require system to be isolated
4. Multiple consents may be lifted for related building work
5. Building alterations may be undertaken without a consent

The first four of these will tend to overestimate the risk for high rise buildings so will lead to a conservative estimate. The latter reduce the estimate but anecdotal evidence suggests that this would not represent a large number for the situation of interest. If building works are significant enough to require isolation of fire protection systems for significant periods of time then it is considered probable that a building consent will be obtained for the work.

CB Richard Ellis refer a total floor area for high rise central business district type commercial office space in New Zealand of 2.5 million m^2 commercial office space (high rise CBD type space).

From consents data sourced from BRANZ (Page, 2007) it is estimated that high rise offices account for 2% of the office building stock (by number of office buildings). If is assumed that the rate of alteration work is proportionate to the number of buildings then this gives a value of approximately 40 alterations per year in high rise office buildings.

Number of high rise office buildings is estimated as 250 from CB Richard Ellis Data and 300 from Quotable Value data. Based upon this the estimated probability of alterations occurring in any given high rise office building in any given year are 0.14. If it is assumed that alterations in high rise buildings are twice as likely as in non high rise buildings the resultant probability is 0.28. As a lower bound it could be assumed that around 50% of alterations will be taking place in unoccupied buildings or where no isolation is required as part of the work. There is a significant uncertainty in these values as the analysis assumes the rate of alterations is comparable across high and low rise offices which may not be correct. There may be reason to suspect the rate of alteration is higher in high rise office buildings. Also it is assumed that the building is occupied and systems will be isolated for duration of work. These factors will tend to overestimate impact of this work so there will be some balancing of effects and the unavailability when all factors considered are expected to be representative.

Concerns over accidental activation may mean that contractors are overly cautious and seek to isolate systems when this is not necessary. Furthermore there is anecdotal evidence that contractors may isolate whole systems (or groups of systems) to be safe from the unwanted consequences of working on a live system, namely water damage, brigade callout, etc. For example a contractor may isolate a system in a high rise building at the main isolate valve rather than simply at the floor isolate valve. This risk may be lessened if the system is one that the contractor has installed so there is greater familiarity and confidence.

Most building activities which require system isolation would be expected to be covered by consent. The exceptions are decorating work such as ceiling painting which may require masking of detectors. This is uncommon for multi-storey office buildings which would not normally have painted ceilings. It is common for apartments. Generally this work will be undertaken whilst the building is unoccupied. It is possible painting may take place on a building floor whilst other floors are occupied in which case this would represent an increased level of risk. Perhaps the greater risk however is of detectors being left impaired following the work either by being clogged with paint or other material or by being left masked. This risk has been identified under detector failure and quantified there.

To illustrate the possible unavailability the work duration has been assumed to range between 1 week (for minor alterations) up to 8 weeks for a major fit-out. Applying this range to the range of expected probabilities of tenancy alterations taking place yields the following unavailability range expressed in terms of 1) the probability of work taking place, the potential unavailability assuming system isolated 24 hours a day and the reduced unavailability assuming system is reinstated at the end of each working day.

Case	**Lower bound**	**Expected**	**Upper bound**
Probability of tenancy work	0.07	0.14	0.28
Potential Unavailability	0.0013	0.011	0.043
Assume system reinstated overnight[42]	0.00031	0.0026	0.010

Table 8.84: Unavailability Probability for High Rise Office Building Due to Building Work

These values may be adjusted down further if it assumed that only the area being worked upon is isolated. This would be expected for alarm systems but may not be the case for sprinkler systems. If a 90% probability is assumed for local isolation to be used for alarm systems and a 70% probability for sprinkler systems, and assuming a typical 10 storey office building the resultant unavailability reduces further to:

Case	**Lower bound**	**Expected**	**Upper bound**
Assume local isolation may be used (alarms)	0.000059	0.00049	0.0019
Assume local isolation may be used (sprinklers)	0.00011	0.00096	0.0037

Table 8.85: Unavailability Probability for High Rise Office Building Due to Building Work Adjusted to Account for Local Isolation

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[42] Implicit assumption that fires are as likely at night and weekends

In practice if the unavailability time is significant in the analysis and/or there is significant deviation from the simplifying assumptions used in deriving these probabilities then a specific analysis for the situation should be undertaken.

Reinstatement Following Damage

Common damage causes are impact to detector or damage to wiring. Risk of this is considered low in office or apartment buildings. Highest potential is when building work is being undertaken and this outage has already been accounted for. This generally has no ongoing impact on availability of the system once in operation, the only exception being if the system is conditionally accepted providing the damage is rectified during the maintenance period. The replacement time for damage is unlikely to be significant compared with the total system isolation time. For these reasons this factor will not be separately accounted for.

Reinstatement Following Fire

Fire probabilities are estimated from the correlation given by VTT.

$$f''_m(A) = c_1 A^r + c_2 A^s \qquad (5)$$

Coefficients for various occupancies given by:

Building Type	c1	c2	r	s
Residential	0.01	5E-6	-1.83	-0.05
Retail	7E-5	6E-6	-0.65	-0.05
Office	0.056	3E-6	-2.00	-0.05
Institutional Care	2E-4	5E-6	-0.61	-0.05
Assembly	0.003	2E-6	-1.14	-0.05
Education	0.003	3E-6	-1.26	-0.05
Industrial	3E-4	5E-6	-0.61	-0.05
Warehouses	3.82	2E-6	-2.08	-0.05

Table 8.85: Fire Start Probability Coefficients for use in Equation 5

For example, given a typical 10,000m^2 office or a 5,000m^2 apartment building the resulting start probabilities are:

Factors	Residential	Office
c1	0.01	0.056
c2	5.00E-06	3.00E-06
r	-1.83	-2
s	-0.05	-0.05
Area	5000	10000
Fire Start Probability/m^2	3.27E-06	1.89E-06
Fire Start Probability	1.63E-02	1.89E-02

Table 8.86: Example Fire Start Probability Values

It is likely that the fire protection system will be able to be quickly put back into operation (say within 8 hours at least for occupied areas, the fire floor may take longer). In this case the indicative unavailability for the two cases are as follows:

Unavailability	**Residential**	**Office**
	1.5E-5	1.7E-5

Table 8.87: Indicative Unavailability Following Fire

These unavailability levels are significantly lower than those associated with the normal testing and maintenance activities on the systems.

There is also the disruption caused by the associated building work to refurbish following fire. The system unavailability resultant from these fires depends on the effectiveness of the fire protection. For simplicity if it is assumed that for a suppression system damage is limited to the fire cell or the smoke cell of origin and water damage to the floors below.

This has already been accounted for (for office buildings) in the unavailability based on building consents. For apartment buildings this is an additional risk. If it is assumed that documentation period is 5 weeks (Rawlinson (2006) lower limit for small value project) and construction period is 8 weeks (extrapolated from Rawlinson) giving an indicative unavailability period of 3 months. This would then equate to an unavailability of 6.7E-4. This is expected to reflect an upper bound for those cases where the system is reinstated at the end of the construction process. For a sprinkler system it is unlikely the system (as a whole) would be impaired for this duration. Use of temporary detection measures could also be used during the construction process to reduce the risk.

Aggregating Unavailability

As discussed above there are various sources of unavailability, including unavailability due to:

- Failure and associated system downtime
- Scheduled testing and maintenance on the system
- Remedial work from surveyed deficiencies
- Down time from failures
- Isolation due to building work

These are summarised for each system type in table 8.88. Indicative arrangements are assumed and unavailability calculated from the information given for individual components and subsystems. The values are indicative for typical arrangements with simplifying assumptions, consideration of requirements of specific arrangements and calculation using specific maintenance and availability information would lead to adjusted values. Lower bounds for maintenance and testing are based on credible maximum durations for work and increased work on survey remedial items.

System	Unavailability Type	Expected	Lower	Upper
Sprinkler System (TM connected)	Testing and Maintenance	6.6E-4	1.3E-2	2E-4
Sprinkler System (TM connected)	Failure downtime	1.1E-4		
Sprinkler System (Diesel pump)	Testing and Maintenance	1.1E-3	2.2E-3	6.4E-4
Sprinkler System (Diesel pump)	Failure downtime	1.5E-4		
Alarm System	Testing and Maintenance	1.1E-3	2.2E-3	3E-4
Alarm System (smoke)	Failure downtime	1.8E-5		
Alarm System (heat)	Failure downtime	1.7E-5		
Sprinkler (in office)	Building Work	1.8E-4	9.6E-4	3.7E-3
Alarm (in office)	Building Work	7.6E-5	5.1E-4	1.9E-3
Any (in apartment)	Building Work	1.5E-5		
SPS	Failure downtime (SPF)	5E-4		
SPS	Testing and maintenance	9.1E-4		
SPS (alarm system downtime) average value	All	1.2E-3		

Table 8.88: Summary of Indicative Unavailability Values by System and Unavailability Cause

Aggregating these yields the following indicative unavailability values (only expected values given):

System	Location	Expected Unavailability	Expected Availability [%]
Sprinkler System (TM connected)	Office	9.5E-4	99.90
Sprinkler System (TM connected)	Apartment	7.8E-4	99.92
Sprinkler System (Diesel pump)	Office	1.4E-3	99.86
Sprinkler System (Diesel pump)	Apartment	1.3E-3	99.87
Alarm System	Office	1.2E-3	99.88
Alarm System	Apartment	1.1E-3	99.89
Stairwell Pressurisation System	All	2.6E-3	99.74

Table 8.89: Summary of Indicative Unavailability Values Aggregated Across Causes

Noting that these are indicative values only and they are based upon specific design arrangements and simplifying assumptions.

Efficacy Criteria

Up until now consideration has been given to reliability and availability. Efficacy has been implicitly included to a limited extent since data of system reliability and peoples estimates of reliability often include efficacy. For example data from OREDA does not differentiate between situations where the detector failed to operate because of the fire characteristics; when people are questioned about pump failure their view will be prejudiced by recollection of situations where a pump failed because of changes in the towns main pressure. It cannot be assumed however that efficacy is accounted for, it will not be. By neglecting efficacy two problems would be introduced; firstly, we would overestimate the chances of success (assuming that efficacy is always less than 100%), secondly, we would not be able to account for efficacy differences due to different design approaches. Efficacy can be included into the analysis in two different ways:

1. Event trees can be used together with fault trees and the efficacy is accounted for by different consequences (or consequence distributions) on each of the sub-scenarios (end points of each branch). For this approach two pieces of information are required. Firstly an approximation of the relationship between specific events (e.g. smouldering fire) and efficacy and secondly a method for quantifying the consequences to allow the level of risk to be established (either absolute or relative risk).
2. Fault trees can be used with a failure mode which accounts for the failure due to efficacy. This failure mode will be a function of the system design and the design scenarios of interest.

There are pros and cons with each method. The first allows explicit consideration of consequences and (arguably) integrates better with quantitative risk based analysis for design where an engineer may use an event tree to define the unwanted consequences for the fire scenarios of interest. It does however require information on the relationship between events and efficacy which is not well defined for many events, and will vary according to fire scenario. Quantification of consequences increases the level of analysis required though if the approach is being used in a wider event tree analysis to define the system reliability components then this is not a major drawback.

The fault tree approach allows a single value (or distribution) to be provided for the reliability, at least for a given design situation. It is therefore simpler to use but does mask the relationship between events and resulting efficacy of systems which may result in a less robust analysis if it is being used in a wider event tree analysis by an engineer as part of a QRA. To some extent this can be overcome by using different reliability values on different branches of the tree. A key example would be the reliability (including efficacy) of a stairwell pressurisation system on two branches of an event tree one where a sprinkler system has operated and one where it has not. A further advantage of this approach is that these derived reliability values can then be used in other risk assessment models such as the available computer models, this is not practical in an event tree approach unless the computer model is able to interface with the outputs from the event tree analysis.

Event Tree Approach

In the event tree approach the simplest case would be where the efficacy associated with events would be 1 or 0, i.e. the system works or it does not. For many event types this is the situation. For example a loss of power event has an efficacy of 0 for an alarm system.

Events can be failure events within the system or they can be external events, including the fire, or the activation of another system or sub-system.

As already discussed efficacy can be considered as a range between 0 and 1, and the product of the two give the overall effectiveness. The overall risk then reflects this change in effectiveness by the change in the relative frequency of each of the sub scenarios. Selecting the value of the efficacy when it is not 0 or 1 is usually subjective. It can be related to the deviation of the outcome from the design ideal or to a subjective measure of the increased risk of the unwanted outcome.

Each efficacy factor is a branch point in the event tree. For example the smouldering fire is explicitly included as an event in the event tree and the likelihood and consequences of the system response are considered explicitly for each branch. The efficacy can then be accounted for (as well as possible given knowledge uncertainty) for each sub-scenario and explicitly considered in terms of its effect on the risk. Where the impact of the efficacy is to simply change the likelihood of the system working or not (as we may assume is the case for a sprinkler protected smouldering fire) then it is simply a matter of change the probabilities of each sub-scenario. In this case a simple efficacy factor can be used to alter the likelihood for the event outcomes. Where however the consequences may be altered then it is necessary to consider the impact of these against the limit state equation for the model. Generally the relationship will not be analytical and will require computer modelling and engineering judgement to assess the impact of the system efficacy on the consequences.

In terms of Kaplan triplets the risk can be expressed by the set:

$$R = s_i, p_i, c_i$$

Where the probabilities p_i and c_i can be single valued or distributions.

Some events will only alter p values, some may alter p and c values. Can use simple efficacy factor on event tree branch likelihoods in former case. In latter case can still use efficacy factors (which alter p) to try to approximate change in c value as well. E.g. first detector failing will alter the possible consequences compared to a set of R where the first detector does not fail. Have introduced additional outcomes. Can approximate this by efficacy factor which provides a simple multiplier to account for the altered consequences due to the event. The benefit of this approach may be marginal if a full QRA is being undertaken however it does provide a means for considering the efficacy of a system for a range of likelihoods rather than simply considering the system as a pass-fail arrangement.

An efficacy factor may be the top level event of a fault tree. For example if our efficacy event is a system not signalling the fire brigade then the likelihood of this would be the top level of a fault tree.

The following table identifies some events (including component and subsystem failures) which may impact on the efficacy of the system. The efficacies in the table are nominal values provided for illustration only as specific research is required to validate these. In general it is considered that the events will have a significant impact on both the likelihood and the range of possible consequences and therefore the use of a simple efficacy factor is an approximation.

System type	Event	System Efficacy	
		Awake	Sleeping
Alarm	First detector fails	90%	50%
Alarm	Brigade signalling fails	90%	80%
Smoke detection	Fast flaming fire	90%	50%
Heat detection, Sprinkler	Smouldering fire	80%[43]	5%
Alarm, sprinkler	Concealed (unprotected) space fire	80%	50%
SPS	Damper fails open	50%	50%
SPS	Damper fails closed	80%	80%
SPS	VSD software failure	80%	80%
SPS	Pressure sensor out of range	80%	80%

Table 8.90: Indicative Efficacy Values (for Illustrative Purposes Only)

Efficacy values are discussed further in the section on fault trees. Much of the discussion in the fault tree section is equally applicable to event tree methods.

Fault Tree Approach

Accounting for Efficacy in the fault tree analysis is achieved by including an additional failure mode at the top level of the fault tree which captures those failures which are explicitly scenario specific. As a very simple example if we were only interested in smouldering fire scenario then the efficacy factor for sprinkler systems would be extremely significant. In the following simplified diagram the lack of efficacy of the sprinkler system when dealing with smouldering fire is represented by the high (95%) inefficacy factor for this specific scenario. This dominates the resulting effectiveness value being far more significant than the on demand reliability or availability of the system. The effectiveness for the system is 1 – 0.961 = 0.039 (NB all values used are nominal for illustration purposes only).

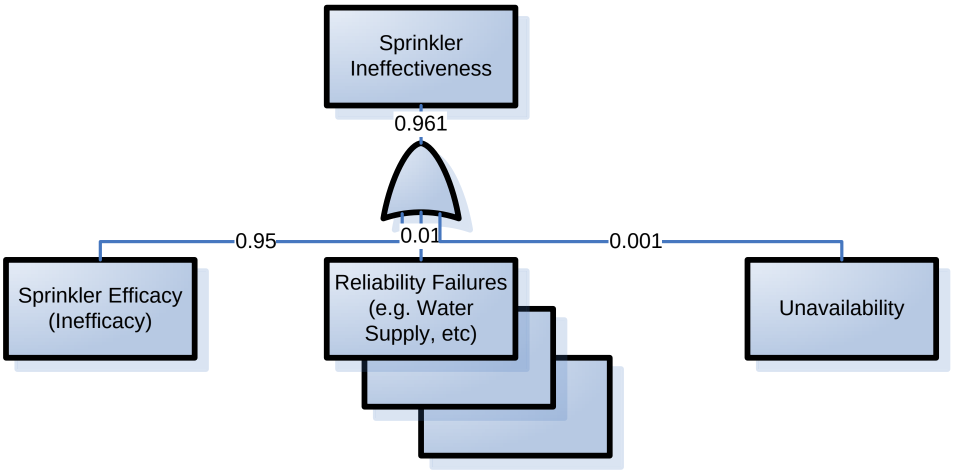

Figure 8.1: Example Fault Tree

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[43] Based on large space where smouldering fire would be expected to develop into a flaming fire without loss of tenability. In small space such as an apartment efficacy is 0% as whether the sprinkler is there or not does not alter the outcome.

If distributions are used then the efficacy can accommodate knowledge uncertainty and natural variability. In the case of the latter rather than the set 0.95 value used in the example above the inefficacy may be allowed to vary between 0.8 and 0.99 (for example) with an expected value of 0.95. Selection of appropriate efficacy ranges is discussed later.

Use of distributions also allows natural variability to be accommodated. For example in the sprinkler example there is data available on the relative frequency of smouldering and flaming fires. For flaming fires the efficacy would be expected to approach 100%, for smouldering fires the efficacy is estimated as being around 5%. The simplest distribution would be a two point distribution as illustrated in figure 8.2.

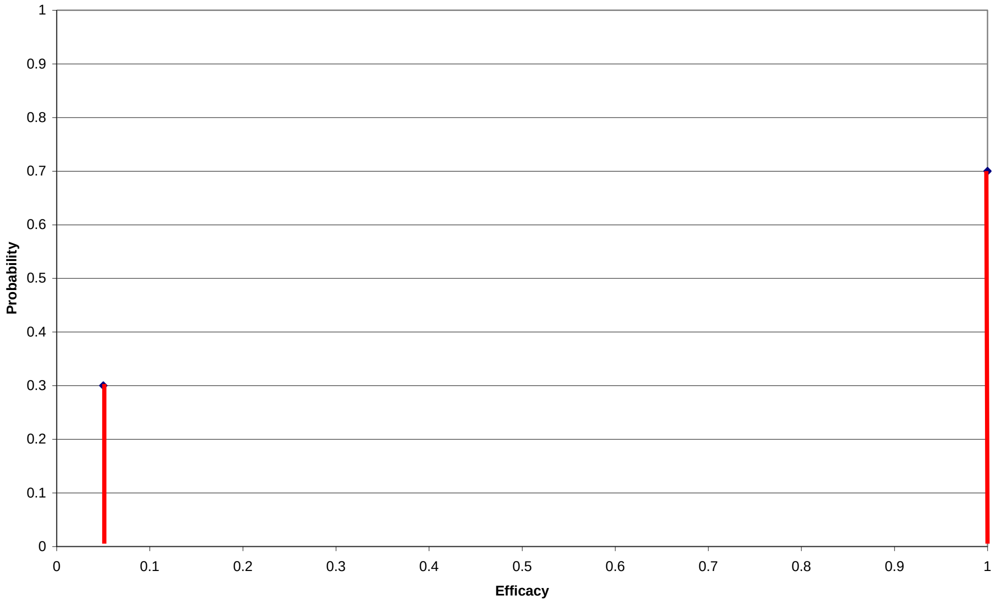


Figure 8.2: Simple Bimodal Efficacy Distribution for a Sprinkler System (nominal)

The distribution could also be represented as a continuous distribution (example figure 8.3) to account for knowledge uncertainty and natural variability in the fire characteristics (fires being not purely smouldering or purely flaming in nature) and natural variability in the system response.

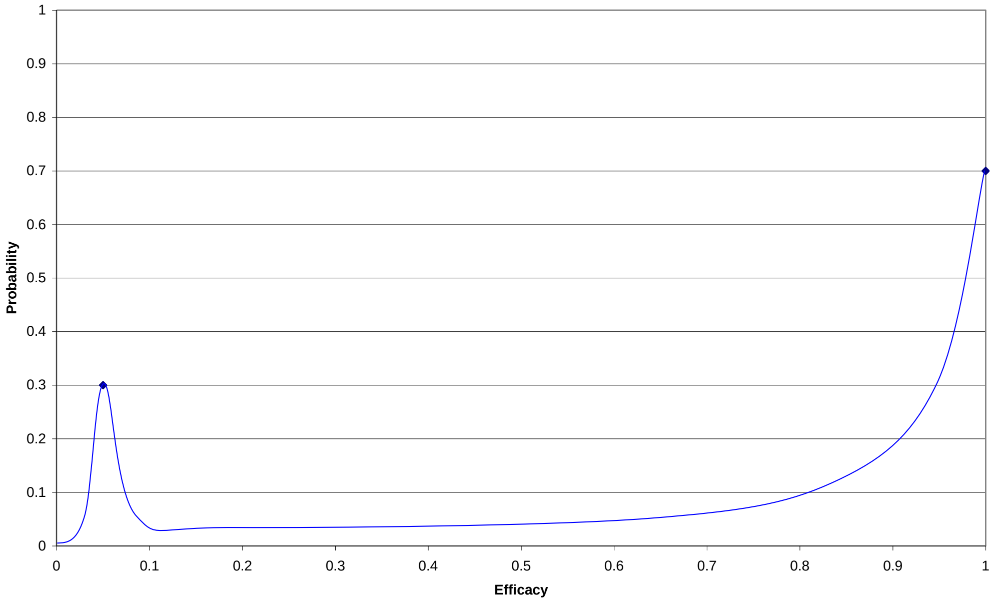


Figure 8.3: Continuous Bimodal Efficacy Distribution for a Sprinkler System (nominal)

Determining Efficacy

Unfortunately data on system efficacy is limited. Some values have been published but the basis of these is uncertain and the efficacy is not related to specific fire scenarios but rather is presented as a general adjustment factor to be applied across all scenarios. In principle efficacy values (or distributions) can be ‘reverse engineered’ from effectiveness data if on demand reliability and availability for the systems are assumed.

For alarm systems and sprinklers there are two key components to efficacy:

1. The reduction in system effectiveness due to the interaction between the fire and the detector. This is the case illustrated in the example of the sprinkler and the smouldering fire. For certain fire characteristics the detectors may not operate or the operation may be compromised. For simplicity it is generally assumed that this measure of efficacy is either pass or fail. Either the detector will operate (satisfactorily) or it will not. This then in effect becomes another failure mode for the system and can be simply included into the fault tree analysis. There is some risk of double counting if detector failure statistics already include failures due to this mode. Fire Service statistics (for example the New Zealand FIRS data) often are dominated by detector failures (particularly heat detectors and sprinklers) due to the fire being too small or being a smouldering fire.

2. The reduction in system effectiveness due to a partial failure. For example the loss of fire brigade signalling is a failure of the system but would not render the system impotent. An alarm would still be raised in the building, sprinklers would still operate. For simplicity these partial failure modes are often treated as critical. This will tend to underestimate system effectiveness. This aspect of efficacy was discussed above in the description of the event tree approach and this method provides one means of allowing for partial system success. When using fault trees the impact of efficacy may be provided by an efficacy factor or distribution.

Each system type is now considered in detail to provide guidance on how efficacy may be estimated.

Sprinkler Systems

The efficacy of sprinkler detectors depends on the fire scenario. Assuming the relative frequency of smouldering fires as 30% and the efficacy of sprinkler systems as 5% for smouldering fires then the efficacy can be approximated by simply combining efficacy for the two fire types in proportion to their frequency. This gives a nominal efficacy for sprinkler systems of 71.5%.

The following table is derived from data presented in the NIST study by Bukowski et al (2007).

Fire Location	Fire Type	Number
Kitchen	Flaming	99909
Living Room	Flaming	7196
Bedroom	Flaming	20465
Total Flaming		**127570**
Living Room	Smouldering	4060
Bedroom	Smouldering	6437
Total Smouldering		**10497**
% Smouldering		**7.6%**

Table 8.91: Proportions of Smouldering and Flaming Fires (Bukowski et al)

As part of the study residential sprinkler response was tested. It was found, as expected, that these did not respond until the fire has transitioned from the smouldering state to a flaming state.

Based upon these proportions the efficacy of sprinkler systems in a residential occupancy is approximately 92.3%.

From the 2006 white paper on home smoke alarms:

"Best estimates are that at most 3% of home fire fatalities involve fires that never transition from smoldering to flaming, and the majority of those are fires where the fatal victim is intimate with ignition, i.e., very close to the point of fire origin"

Based upon a 3% estimate of smouldering fires the resultant sprinkler system efficacy is 97.1%

In an office type environment providing that the person is not intimate with the fire and unaware of it (which is considered unlikely) the critical issue for efficacy is the proportion of fires which never progress beyond the smouldering stage. For these scenarios the system will not operate and therefore the efficacy is minimal. If a fire in an office type environment transitions to the flaming stage the sprinkler will operate and will be effective in preventing fire growth and in controlling tenability.

Efficacy estimates for sprinklers have been derived by Watanabe who suggests values of 99.9% (inefficacy of 0.001). This value is suggested as an upper bound but only for non sleeping occupancies.

From the above it is suggested that the inefficacy range for sprinkler systems due to smouldering fires is as follows:

System	Occupancy	Expected	Lower	Upper
Sprinkler System	Residential (sleeping)	0.077	0.285	0.029
Sprinkler System	Office	0.029	0.077	0.001

Table 8.92: Inefficacy due to smouldering fires

There is also the risk of a fire starting in a concealed space which is not sprinkler protected. From Ahrens (2007) 2% of residential fires (including apartments) started in concealed spaces. It is possible that if a fire starts in an unprotected concealed space then untenable conditions could occur prior to sprinkler activation (i.e. before the smouldering fire transitions to a flaming fire and breaks out of the concealed space). For a specific risk assessment this likelihood could be adjusted to account for the construction, the level of protection and the likelihood of a fire developing in the concealed space. For illustrative purposes we will assume that 50% of apartment buildings have concealed ceiling spaces and 50% of those are unprotected therefore giving an expected 0.5% risk of failure. Lower bound taken as 1% and upper bound as 0.25%.

For office buildings the occurrence of concealed spaces is arguably higher but these are also more likely to be protected. The inefficacy has been kept the same as for residential occupancies.

System	**Occupancy**	**Expected**	**Lower**	**Upper**
Sprinkler System	Residential (sleeping)	0.005	0.01	0.0025
Sprinkler System	Office	0.005	0.01	0.0025

Table 8.93: Inefficacy (nominal values) due to concealed space fires

Shielding of fires can also result in reduced efficacy of sprinklers. If the fire is a flaming fire it would be expected that the system would still operate but that operation might be delayed. No conclusive data exists on the impact of shielding on system efficacy. The most credible case of a shielded fire for a residential occupancy might be a fire in a cupboard space containing electrical equipment. A well known example being the clothes dryers in cupboards which are relatively common in apartments. Ahrens (2007) reports on these represent 2% of all fire types and if the cupboard space is not sprinkler protected then this represents a credible fire risk and would have a direct impact on system efficacy. It is assumed that a proportion of all such dryer cupboards, etc, would be adequately protected (say 50%) to give an expected value of 1%.

In office occupancies the credible shielded fire scenarios may be a fire under a desk. Whilst these might cause delayed response and limit effectives of control there is no conclusive evidence that this constitutes a significant loss of efficacy.

System	**Occupancy**	**Expected**	**Lower**	**Upper**
Sprinkler System	Residential (sleeping)	0.01	0.02	0.001
Sprinkler System	Office	0.001	0.01	0.0001

Table 8.94: Inefficacy (nominal values) due to shielded fires

There are a number of other factors which could modify the efficacy of a sprinkler system. The most significant of these is the potential for dropping of town main pressure. The likelihood of this is high with estimates of up to 10% of surveyed towns main systems failing because of this reason. If this is a significant issue for any given design decision then it would be expected that a specific risk assessment be undertaken to investigate the impact this may have on system efficacy. The impact of pressure drops in the towns main is mitigated by a number of factors. Firstly the number of sprinklers operating for the majority of cases will be a fraction of the design number. Secondly the pressure drop will normally only impact on those sprinklers remote from the valveset.

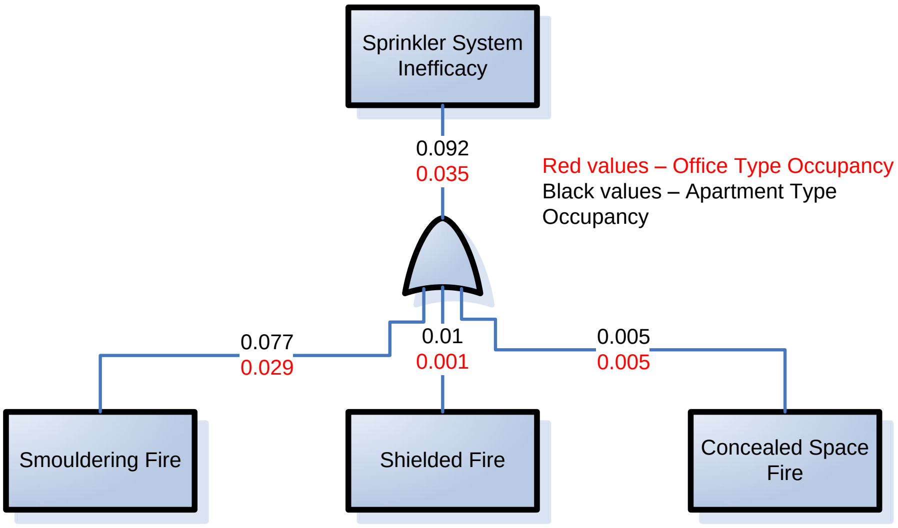


Figure 8.4: Sprinkler System Inefficacy [Nominal Expected Values]

Based on the expected values used the overall inefficacy for a sprinkler system is 0.092 for apartment type occupancies and 0.032 for office type occupancies. This corresponds to efficacy values of 90.8% and 96.5% respectively.

Heat Detectors

Issues with heat detectors are similar to those for sprinklers. Smouldering fires would not be expected to operate heat detectors. The efficacy for these will be assumed to be the same as for sprinklers:

System	Occupancy	Expected	Lower	Upper
Heat Detectors	Residential (sleeping)	0.077	0.285	0.029
Heat Detectors	Office	0.029	0.077	0.001

Table 8.95: Inefficacy due to smouldering fires

Behaviour for shielded fires would again be equivalent to sprinklers.

System	Occupancy	Expected	Lower	Upper
Heat Detectors	Residential (sleeping)	0.01	0.02	0.001
Heat Detectors	Office	0.001	0.01	0.0001

Table 8.96: Inefficacy (nominal values) due to shielded fires

The concealed space coverage of these devices is assumed to be the same as for sprinklers leading to the following nominal values for efficacy due to concealed space fires.

System	Occupancy	Expected	Lower	Upper
Heat Detectors	Residential (sleeping)	0.005	0.01	0.0025
Heat Detectors	Office	0.005	0.01	0.0025

Table 8.97: Inefficacy (nominal values) due to concealed space fires

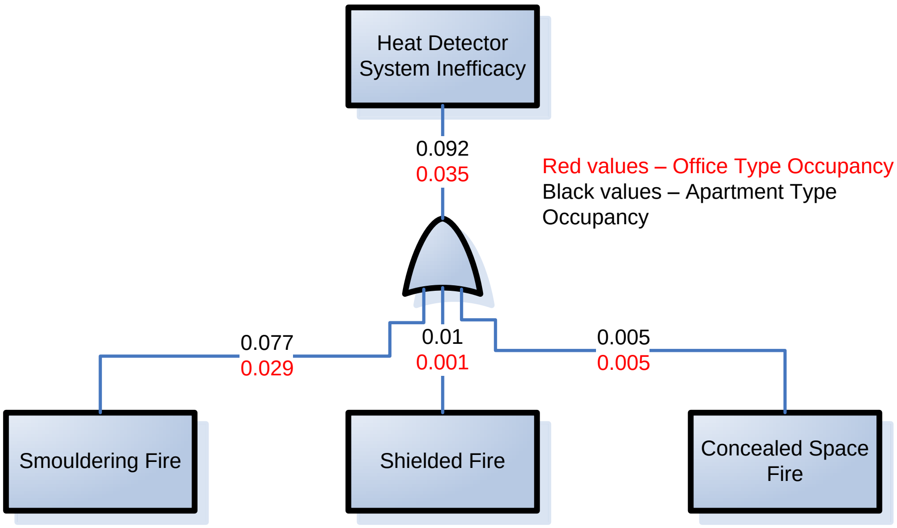


Figure 8.5: Heat Detector System Inefficacy [Nominal Expected Values]

Based on the expected values used the overall inefficacy for a heat detection system is 0.092 for apartment type occupancies and 0.032 for office type occupancies. This corresponds to efficacy values of 90.8% and 96.5% respectively.

Smoke Detectors

As with sprinkler systems the efficacy of smoke detection systems does vary depending on the nature of the fire. Different detector types respond differently to smouldering fires, flaming fires and fire producing high levels of CO.

Various researchers have looked at reliability of detector response, the following table summarises the inefficacy for detector types for smouldering and flaming fire:

Study	Detector Type	Smouldering Fire	Flaming Fire
Grosse et al	Ionisation	56%	20%
	Photoelectric	4.1%	4.0%
Rose-Pehrson et al	Ionisation	57%	7.7%
	Photoelectric	36%	15%
	Combination	36%	7.7%

Table 8.98: Efficacy of Smoke Detectors from Research of Grosse et al, Rose-Pehrson et al

Many of the fires tested in studies were highly challenging. This is not surprising since the purpose was to differentiate between the performance levels of different technologies.

The major study into smoke detector effectiveness by Bukowski et al did not conclude that there were significant levels of inefficacy with either ionisation, photoelectric, or CO detectors. The scenarios considered were based on NFIRS data of likely fire scenarios in the residential environment and included smouldering and flaming fires.

If detector failures to respond are analysed they show approximate failure rates of 30% for smouldering fires (for either detector type), 20% failure rates for photoelectric detectors with flaming fires and 10% for ionisation detectors with flaming fires. This includes detectors remote from the fire.

If only detectors in the fire room or directly communicating spaces are counted then the results alter. Smouldering fire rates stay at the same level (30%) but flaming fire failure rates drop to 5% for photoelectric detectors and 3% for ionisation detectors. If only detectors within the fire room are considered (not communicating spaces) the failure rates for smouldering fires drop further with no recorded failures for photoelectric detectors and 7% failures for ionisation detectors.

Measurements were also made of tenability considerations. Based on tenability criteria efficacy it was concluded that all detector arrangements tested would (on average) be expected to allow for life safety with only one case of with ionisation detection and a smouldering fire being commented on.

Based on the above discussion the following efficacy values are suggested:

Detector Type	**Smouldering Fire**			**Flaming Fire**		
	Expected	**Lower**	**Upper**	**Expected**	**Lower**	**Upper**
Ionisation	0.1	0.30	0.01	0.05	0.10	0.01
Photoelectric	0.05	0.30	0.01	0.1	0.20	0.01

Table 8.99: Efficacy Values for Smoke Detectors based on Fire Room Performance Only

This is conservative as it is on a per detector basis rather than a system bases. It is appropriate for design purposes as it cannot be (normally) assumed that detectors outside of the fire room will be exposed to the effects of fire. If the design is such where this can be guaranteed the efficacy may need to be adjusted perhaps by including the efficacy of detectors outside of the fire room. This may result in combined system efficacy as summarised in Table 8.100. This was obtained by taking the product of the fire room efficacy and the efficacy of detectors outside of the fire room (based on Ahrens data).

Detector Type	**Smouldering Fire**			**Flaming Fire**		
	Expected	**Lower**	**Upper**	**Expected**	**Lower**	**Upper**
Ionisation	0.03	0.10	0.003	0.005	0.01	0.001
Photoelectric	0.015	0.10	0.003	0.02	0.04	0.002

Table 8.100: Effectiveness of Smoke Detectors Outside of Fire Room

For illustrative purposes if we consider the likely proportion of smouldering fires (7.7%) then the overall efficacy can be approximated as shown in Table 8.101 (only expected values shown) :

Detector Type	**Smouldering Fire**	**Flaming Fire**	**Total Inefficacy**
Ionisation	0.0077	0.046	0.054
Photoelectric	0.0038	0.092	0.096

Table 8.101: Indicative Inefficacy Assuming Certain Proportion of Smouldering Fires

This illustrates the importance of this factor in the overall reliability of systems. A full analysis for design would be better undertaken using an event tree analysis where smouldering fire is identified as an event in the tree and the distributions applied for smouldering fire probability and system efficacy. For an office type occupancy the above values would be expected to be conservative (as expected values) as they assume that non response to a smouldering fire is unacceptable and do not allow for a proportion of smouldering fires that may transition to flaming fires and then be detected.

Stairwell Pressurisation Systems

Efficacy of stairwell pressurisation systems is complex. Moore and Tims reported reliability for assumed efficacy levels which were based upon component performance in systems. The fault trees produced by Fazio did not include efficacy explicitly but in addition to the normal component failures in the fault tree there was an additional component to cater for poor overall system performance.

Fazio also examined the impact of natural variables on system performance for example wind, temperature and construction tightness.

There has also been research undertaken by Taylor looking at the impact of sprinkler system operation in combination with stairwell pressurisation.

None of the research is of a form which allows any quantification of pressurisation system efficacy to be concluded. It is proposed that the uncertainty in efficacy be dealt with in the overall analysis considering component reliability and natural variability.

Specific analysis on a per design basis would be able to examine the sensitivity of the design to natural variations. This could then be used as a basis for determining the efficacy of a given design. This could then be included as part of an overall event tree analysis to ascertain the level of risk.

Effectiveness

To establish the overall effectiveness of systems the on demand reliability, availability and efficacy are combined, or more accurately the unreliability, the unavailability and the inefficacy to give the ineffectiveness of the system. This can be done using fault trees (as presented here) or by including into an event tree analysis. An example of a typical fault tree combining the various component parts is shown in figure 8.6.

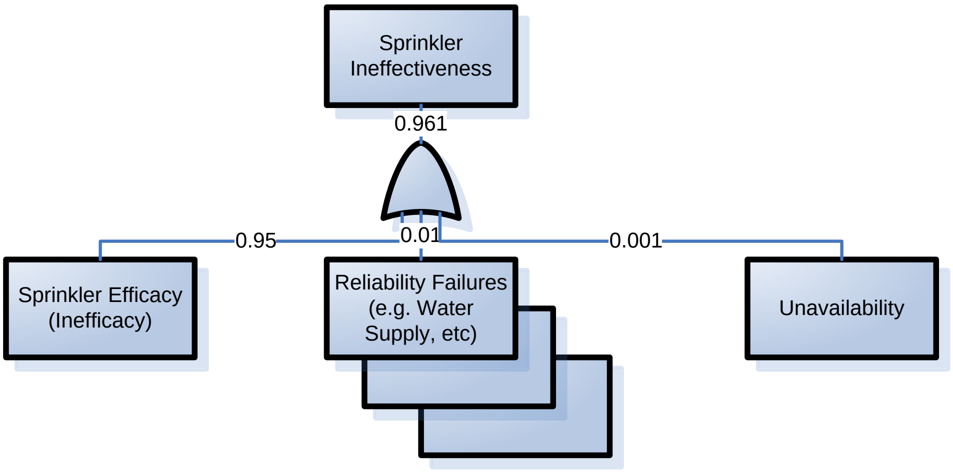


Figure 8.6: Example Fault Tree

The effectiveness of systems is a function of the system design, as discussed at the beginning of this section when candidate designs were discussed. Specific design combinations have been selected. For designs outside of the range of combinations or where the assumptions in the analysis are not appropriate specific analysis is required.

In the remainder of this section the overall effectiveness for a number of candidate designs for each main system type is evaluated.

Sprinkler Systems

Reliability

Figure 8.7 shows a typical fault tree for a simple system. Further reliability fault trees are included in Appendix B. Lower bound, upper bound and expected values are shown. For each group of three numbers the upper bound is the top number, the expected value is the middle of the three, and the lower bound is the bottom number.

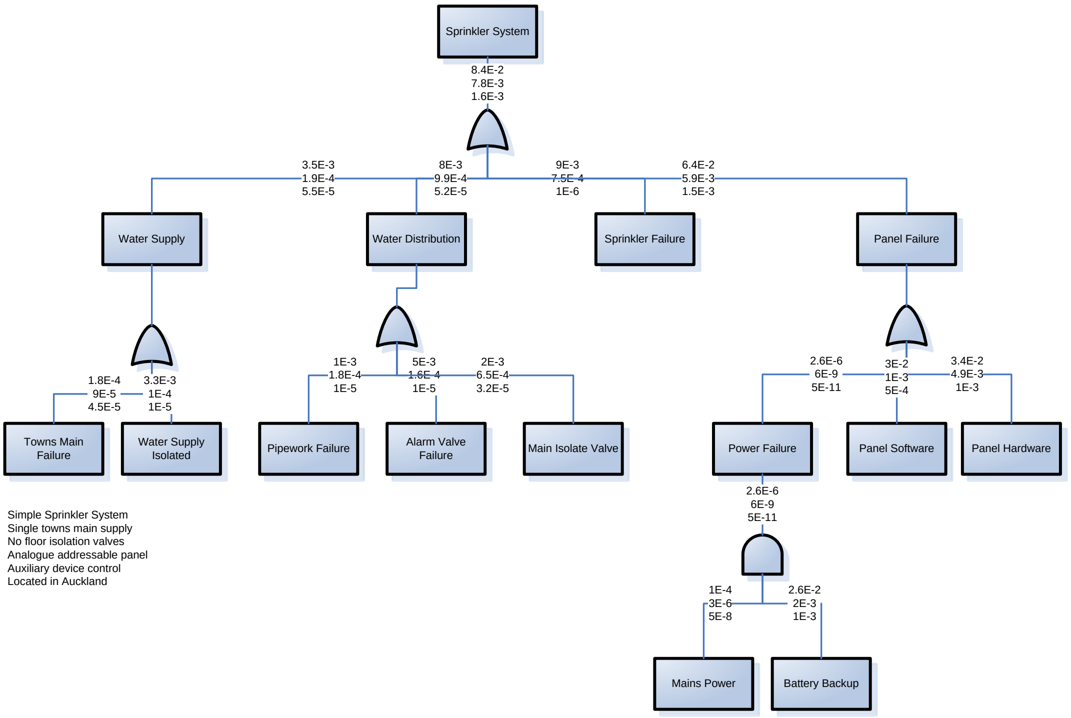


Figure 8.7: Example Reliability Fault Tree

Table 8.102 provides summary reliability data for the fault trees developed for sprinkler systems.

Design Scenario			**Reliability**		
Water Supply	Location	Alarm	Expected	Upper	Lower
Single towns main supply	Auckland	Analogue Addressable	7.8E-3	8.4E-2	1.6E-3
Diesel Pump and Tank Supply	Any	Analogue Addressable	1.1E-2	0.23	2.4E-3
Dual supply: Diesel pump and tank; towns main	Auckland	Analogue Addressable	6.1E-3	8.1E-2	1.5E-3

Table 8.102: Sprinkler System Reliability for Selected Designs

Availability

Typical values for availability are replicated below:

System	Cause	Expected	Lower	Upper
Sprinkler System (TM connected)	Testing and Maintenance	6.6E-4	1.3E-2	2E-4
Sprinkler System (TM connected)	Failure downtime	1.1E-4		
Sprinkler System (Diesel pump)	Testing and Maintenance	1.1E-3	2.2E-3	6.4E-4
Sprinkler System (Diesel pump)	Failure downtime	1.5E-4		
Sprinkler (in office)	Building Work	1.8E-4	9.6E-4	3.7E-3
Sprinkler (in apartment)	Building Work	1.5E-5		

Table 8.103: Sprinkler System Availability for Selected Designs

Efficacy

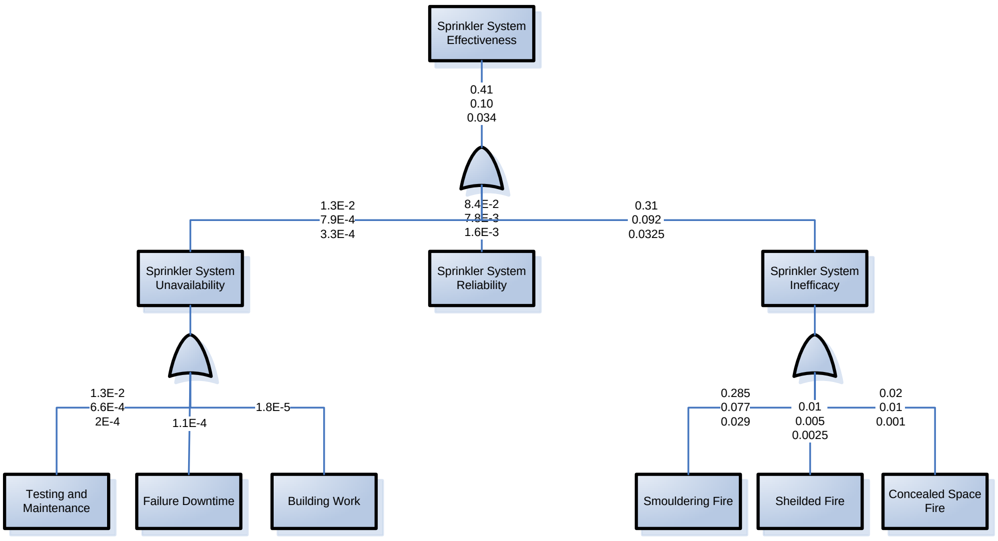
The efficacy of sprinkler systems is dependent on a number of factors three of the key ones are sprinkler lack of response or delayed response due to:

- Smouldering fires
- Fires in unprotected concealed spaces
- Shielded fires

Inefficacy due to smouldering fires				
System	**Occupancy**	**Expected**	**Lower**	**Upper**
Sprinkler System	Residential (sleeping)	0.077	0.285	0.029
Sprinkler System	Office	0.029	0.077	0.001
Inefficacy due to shielded fires				
System	**Occupancy**	**Expected**	**Lower**	**Upper**
Sprinkler System	Residential (sleeping)	0.005	0.01	0.0025
Sprinkler System	Office	0.005	0.01	0.0025
Inefficacy due to concealed space fires				
System	**Occupancy**	**Expected**	**Lower**	**Upper**
Sprinkler System	Residential (sleeping)	0.01	0.02	0.001
Sprinkler System	Office	0.001	0.01	0.0001

Table 8.104: Inefficacy (Nominal Values) Due to Smouldering, Shielded and Concealed Space Fires

An example fault tree combining the reliability, unavailability and inefficacy to give system ineffectiveness is shown in Figure 8.8 below. Further fault trees for systems ineffectiveness are provided in Appendix C.



Towns main single supply
Auckland
Analogue Addressable Panel
Apartment

Figure 8.8: Example Fault Tree for Sprinkler System Effectiveness

Summary results for the nominal effectiveness for a number of typical design scenarios is shown in Table 8.105.

Design Scenario				**Effectiveness [%]**		
Water Supply	Location	Alarm	Occupancy	Expected	Lower	Upper
Single towns main supply	Auckland	Analogue Addressable	Apartment	90%	59%	96.6%
			Office	95.6%	81%	99.4%
Diesel Pump and Tank Supply	Any		Apartment	90%	46%	96.5%
			Office	95.3%	67%	99.3%
Dual supply: Diesel pump and tank; towns main	Auckland		Apartment	90%	61%	96.6%
			Office	95.9%	89%	99.5%

Table 8.105: Effectiveness Values for a Range of Typical Design Scenarios

If the impact of smouldering fires on the effectiveness is taken out of consideration then the results for apartments are changed markedly as can be seen in table 8.106 where effectiveness for apartments and offices is now similar.

Design Scenario				**Effectiveness [%]**		
Water Supply	Location	Alarm	Occupancy	Expected	Lower	Upper
Single towns main supply	Auckland	Analogue Addressable	Apartment	98.0%	87%	99.5%
			Office	98.5%	89%	99.5%
Diesel Pump and Tank Supply	Any		Apartment	97.7%	74%	99.4%
			Office	98.2%	75%	99.4%
Dual supply: Diesel pump and tank; towns main	Auckland		Apartment	98.3%	89%	99.5%
			Office	98.8%	97%	99.6%

Table 8.106: Effectiveness Values for a Range of Typical Design Scenarios (no Smouldering)

Heat Detection Systems

Reliability

Figure 8.9 below shows a typical fault tree for a simple system. Further reliability fault trees are included in Appendix B.

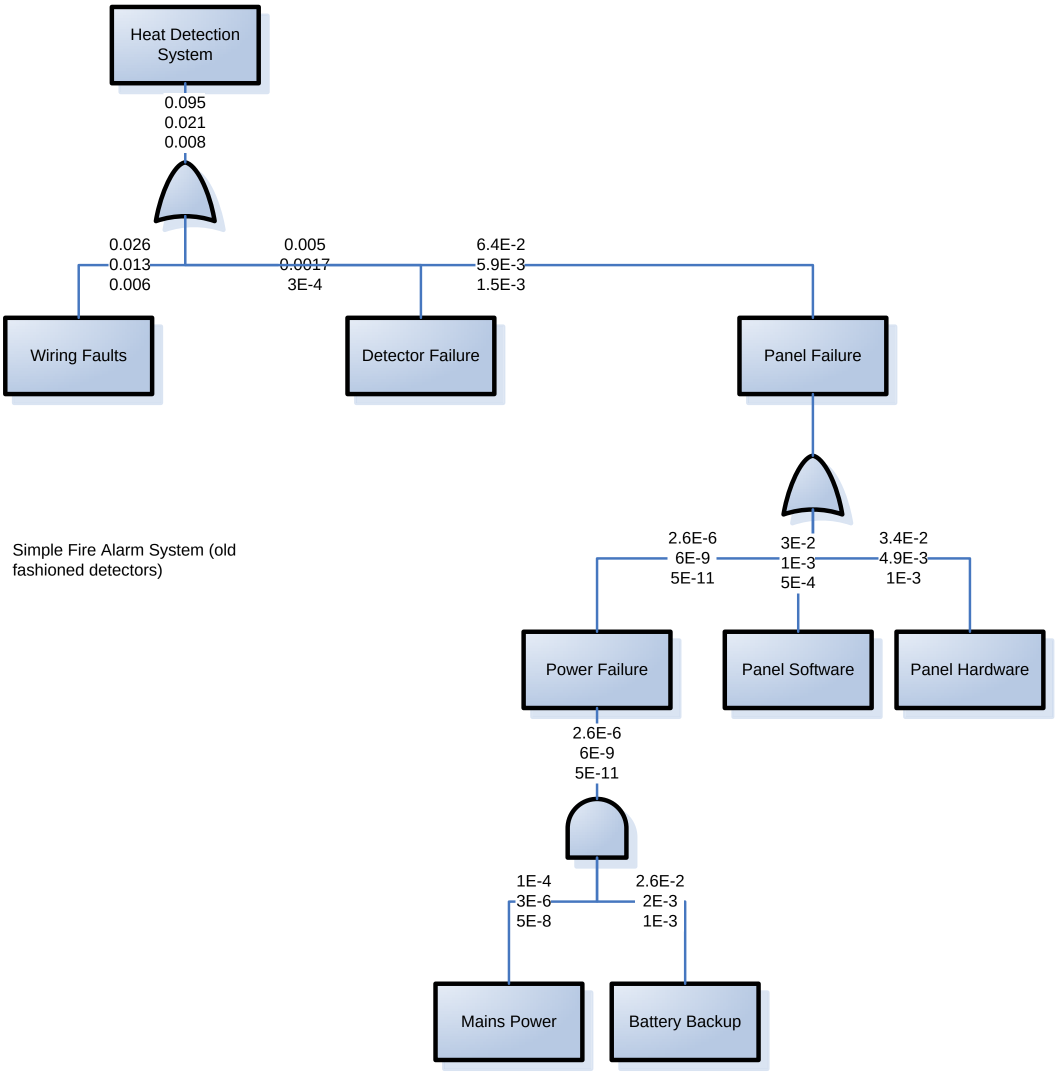


Figure 8.9: Example Fault Tree for Heat Detection System

Summary reliability values for a number of design configurations is given in table 8.107. The old in brackets refers to the use of old style eutectic alloy heat detectors which are inherently less reliable. It is not expected that these would be used in any new system. The complex system refers to a highly complex addressable panel configuration where there is substantial complexity in the software. The lower reliability to a significant extent represents the probability of errors being introduced in the algorithm and the hardware installation. The reliability values would be expected to represent a worst case situation.

Design Scenario	Unreliability			Reliability [%]		
	Expected	Upper	Lower	Expected	Lower	Upper
Simple system configuration (old)	0.021	0.095	0.008	97.9	90.5	99.2
Simple system configuration	0.019	0.092	0.008	98.1	90.8	99.2
Complex system configuration	0.12	0.32	0.008	88	68	99.2

Table 8.107: Heat Detection System Reliability for Selected Designs

Availability

Typical values for availability for heat detection systems are replicated in table 8.108:

System	Unavailability Type	Expected	Lower	Upper
Alarm System	Testing and Maintenance	1.1E-3	2.2E-3	3E-4
Alarm System (heat)	Failure downtime	1.7E-5		
Alarm (in office)	Building Work	7.6E-5	5.1E-4	1.9E-3
Any (in apartment)	Building Work	1.5E-5		

Table 8.108: Heat Detection System Availability

Efficacy

Issues with heat detectors are similar to those for sprinklers. Smouldering fires would not be expected to operate heat detectors. The efficacy for these will be assumed to be the same as for sprinklers:

Inefficacy due to smouldering fires				
System	**Occupancy**	**Expected**	**Lower**	**Upper**
Heat Detectors	Residential (sleeping)	0.077	0.285	0.029
Heat Detectors	Office	0.029	0.077	0.001
Inefficacy due to shielded fires				
System	**Occupancy**	**Expected**	**Lower**	**Upper**
Heat Detectors	Residential (sleeping)	0.005	0.01	0.0025
Heat Detectors	Office	0.005	0.01	0.0025
Inefficacy due to concealed space fires				
System	**Occupancy**	**Expected**	**Lower**	**Upper**
Heat Detectors	Residential (sleeping)	0.01	0.02	0.001
Heat Detectors	Office	0.001	0.01	0.0001

Table 8.109: Inefficacy (Nominal Values) Due to Smouldering, Shielded and Concealed Space Fires

An example fault tree combining the reliability, unavailability and inefficacy for a heat detection system is shown in figure 8.10.

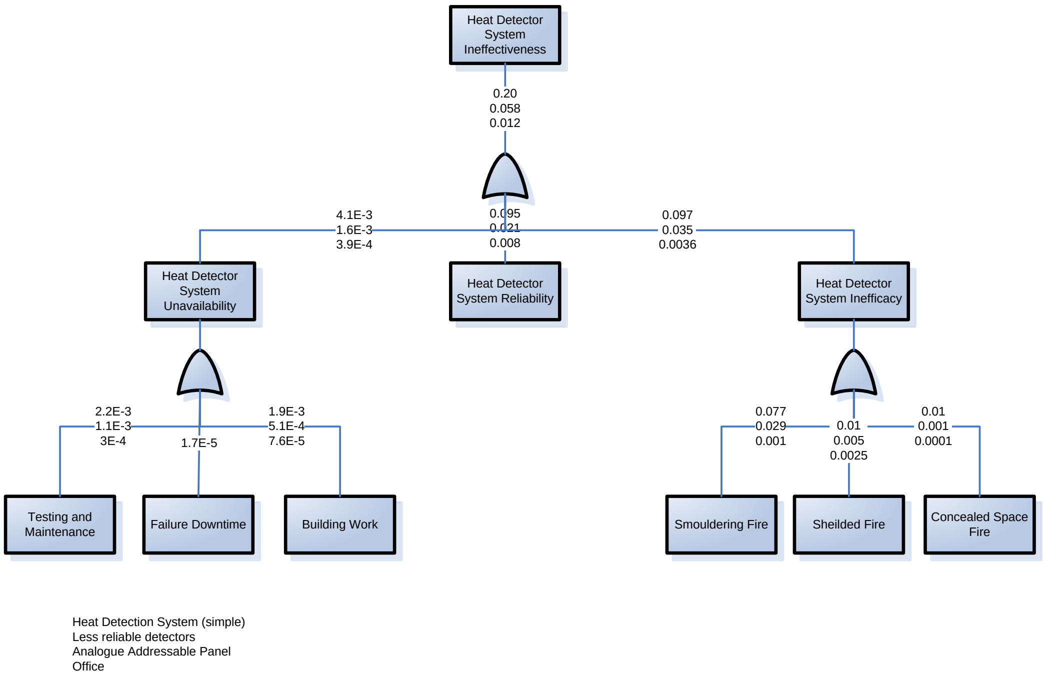


Figure 8.10: Example Fault Tree Showing Effectiveness for Heat Detection Systems

Summary results for the nominal effectiveness for a number of typical design scenarios is shown in Table 8.110.

Design Scenario		**Effectiveness [%]**		
Design	Location	Expected	Lower	Upper
Simple Alarm (old)	Office	94.2%	80%	98.8%
Simple Alarm (old)	Apartment	88.6%	59%	95.7%
Simple Alarm (new)	Office	94.4%	81%	99.5%
Simple Alarm (new)	Apartment	88.8%	59%	96.0%
Complex Alarm	Office	84%	58%	98.8%
Complex Alarm	Apartment	79%	38%	96.0%

Table 8.110: Summary of Effectiveness of a Heat Detection System for a Number of Design Situations

If impact of including smouldering fire scenarios is separated out then the effectiveness changes as shown in Table 8.111:

Design Scenario		**Effectiveness [%]**		
Design	Location	Expected	Lower	Upper
Simple Alarm (old)	Office	97.1%	87.7%	98.9%
Simple Alarm (old)	Apartment	96.3%	87.5%	98.6%
Simple Alarm (new)	Office	97.3%	88.7%	99.6%
Simple Alarm (new)	Apartment	96.5%	87.5%	98.9%
Complex Alarm	Office	86.9%	65.7%	98.9%
Complex Alarm	Apartment	86.7%	66.5%	98.9%

Table 8.111: Summary of Effectiveness of a Heat Detection System for a Number of Design Situations (Excluding Smouldering)

Smoke Detection Systems

Reliability

Figure 8.11 below shows a typical fault tree for a simple smoke detection system. Further reliability fault trees are included in Appendix B.

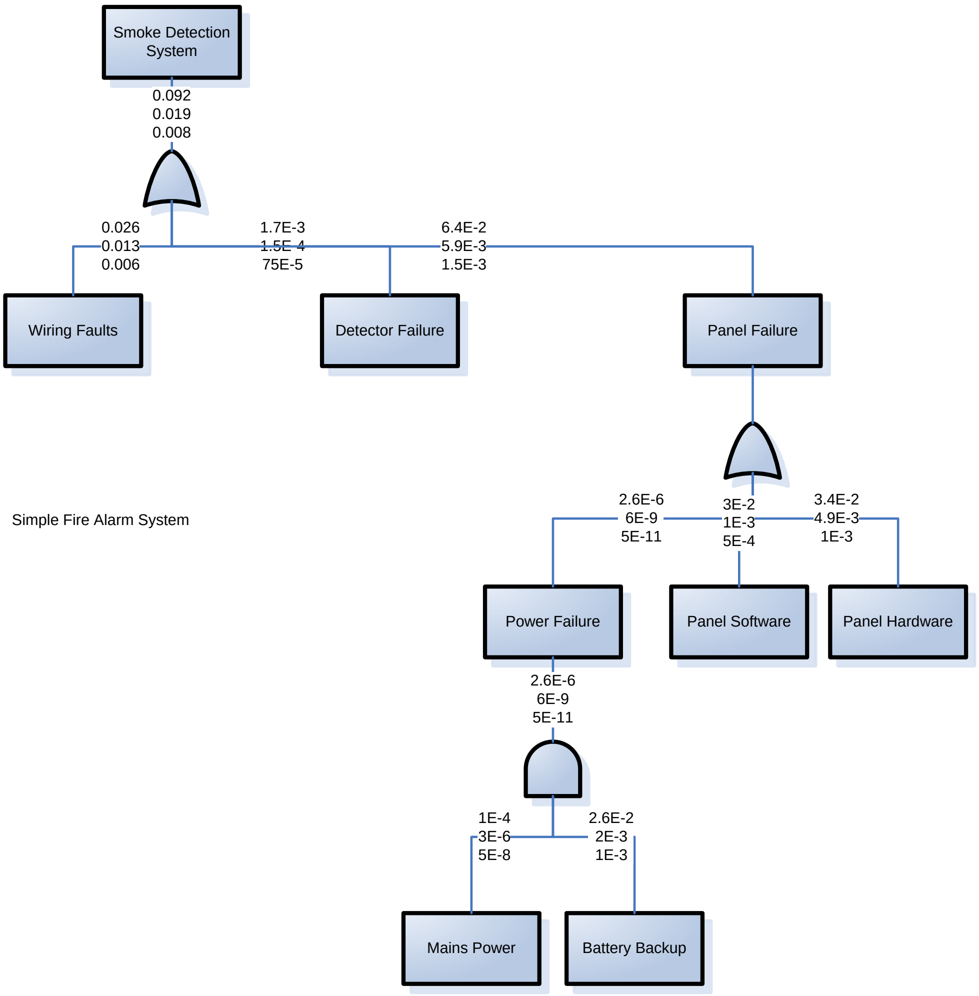


Figure 8.11: Example Fault Tree for Smoke Detection System Reliability

The summary reliability values are given for two cases; a simple system configuration appropriate for small to medium sized projects with limited configuration and interfacing associated with the alarm system, and complex system configuration appropriate for large projects with significant interfacing and complex programming associated with the panel.

Design Scenario	Unreliability			Reliability [%]		
	Expected	Upper	Lower	Expected	Lower	Upper
Simple system configuration	0.019	0.090	0.008	98.1%	90%	99.2%
Complex system configuration	0.12	0.28	0.008	88%	72%	99.2%

Table 8.112: Summary of Reliability Values for Smoke Detection Systems

Availability

Typical values for availability of smoke detection systems are replicated below in Table 8.113:

System	Unavailability Type	Expected	Lower	Upper
Alarm System	Testing and Maintenance	1.1E-3	2.2E-3	3E-4
Alarm System (smoke)	Failure downtime	1.8E-5	-	-
Alarm (in office)	Building Work	7.6E-5	5.1E-4	1.9E-3
Any (in apartment)	Building Work	1.5E-5	-	-

Table 8.113: Smoke Detection System Availability

Efficacy

The efficacy of smoke detection systems is largely dependent on the detector type and the fire characteristics. For simplicity only two basic fire types and two generic detector types are considered.

The following table summarises the efficacy. It is based on detectors in the room of fire origin only and therefore is appropriate for 'bedroom door closed' analysis and would be the recommended efficacy values for sleeping occupancies.

Detector Type	Smouldering Fire			Flaming Fire		
	Expected	Lower	Upper	Expected	Lower	Upper
Ionisation	0.1	0.30	0.01	0.05	0.10	0.01
Photoelectric	0.05	0.30	0.01	0.1	0.20	0.01

Table 8.114: Smoke Detection System Efficacy

Where it is likely that additional detectors beyond the room of fire origin may be able to provide an effective alarm (for example non sleeping occupancies or open plan sleeping occupancies) then an allowance has been made for a secondary activation from these detectors. The efficacy of these are lower than the detectors in the room of origin (based on data from Ahrens). This does not reflect common causes for loss of efficacy so would be expected to represent a lower bound with the true effectiveness (or effectiveness distribution) somewhere between the two cases.

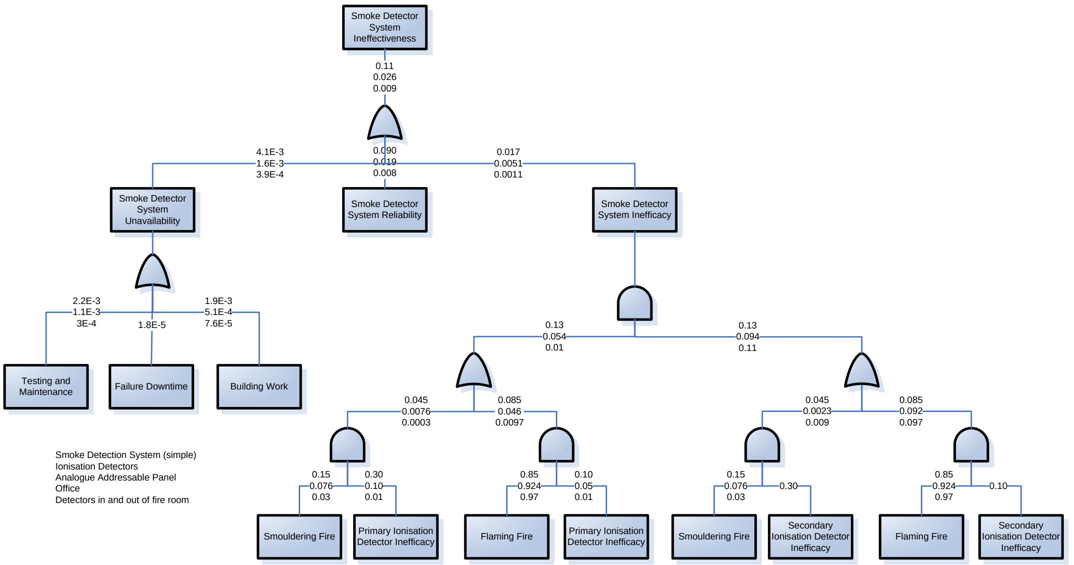


Figure 8.12: Example Smoke Detection System Effectiveness

Summary results for the nominal effectiveness for a number of typical design scenarios for smoke detection systems are shown in Table 8.115.

Design Scenario				**Effectiveness [%]**		
Building Type	Detectors	Design	Open Plan	Expected	Lower	Upper
Apartment	Photoelectric	Simple	No	88%	69%	98.2%
	Ionisation	Simple	No	92.6%	78%	98.2%
	Photoelectric	Complex	No	78%	46%	99%
	Ionisation	Complex	No	82%	53%	99%
	Photoelectric	Simple	Yes	96.2%	86%	99%
	Ionisation	Simple	Yes	97.5%	89%	99%
	Photoelectric	Complex	Yes	86%	63%	99%
	Ionisation	Complex	Yes	87%	67%	99%
Office	Photoelectric	Simple	Yes	96.2%	86%	99%
	Ionisation	Simple	Yes	97.5%	89%	99%
	Photoelectric	Complex	Yes	86%	63%	99%
	Ionisation	Complex	Yes	87%	67%	99%

Table 8.115: Summary of Effectiveness for Smoke Detection System Design Options

Stairwell Pressurisation System

Reliability

Figure 8.13 below shows a typical fault tree for a simple stairwell pressurisation system. Further reliability fault trees are included in Appendix B.

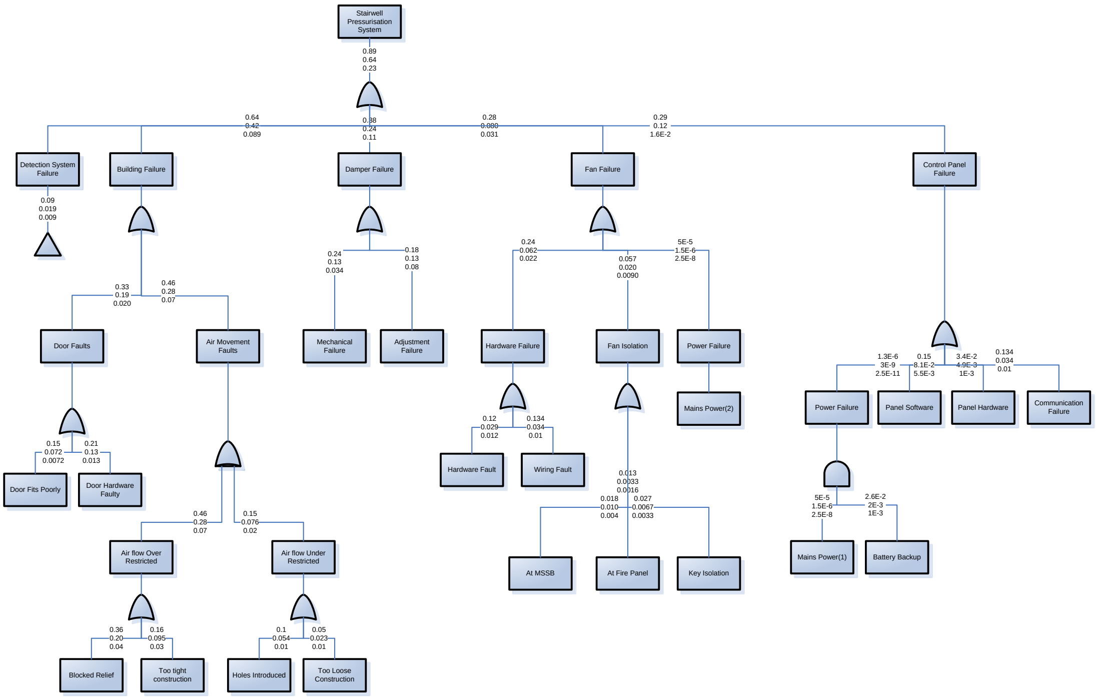


Figure 8.13: Example Fault Tree for Stairwell Pressurisation System Reliability

Summary reliability data for selected design options is presented below. A typical photoelectric smoke detection system has been assumed as the activation system for the stairwell pressurisation system.

Design Scenario	Unreliability			Reliability [%]		
	Expected	Upper	Lower	Expected	Lower	Upper
Fixed speed fan and barometric dampers	0.64	0.89	0.23	36%	11%	77%
Variable Speed drive system	0.72	0.94	0.27	28%	6%	73%
Variable Speed drive and motorised damper system	0.69	0.93	0.26	31%	7%	74%

Table 8.116: Stairwell Pressurisation System Reliability for Selected Designs

If the construction aspects (stairwell tightness and door hardware) are removed from the fault tree so we look solely at system performance then the reliabilities improve markedly.

Design Scenario	Reliability [%]		
	Expected	Lower	Upper
Fixed speed fan and barometric dampers	60%	28%	84%
Variable Speed drive system	47%	14%	80%
Variable Speed drive and motorised damper system	52%	16%	82%

Table 8.117: Stairwell Pressurisation System Reliability for Selected Designs (Excluding Construction Effects)

Unavailability

System unavailability is summarised in Table 8.118 for the stairwell pressurisation system and the alarm system (assumed to be smoke for illustrative purposes) it is dependent upon.

System	Unavailability Type	Expected	Lower	Upper
Alarm System	Testing and Maintenance	1.1E-3	2.2E-3	3E-4
Alarm System (smoke)	Failure downtime	1.8E-5		
Alarm System (heat)	Failure downtime	1.7E-5		
Alarm (in office)	Building Work	7.6E-5	5.1E-4	1.9E-3
Any (in apartment)	Building Work	1.5E-5		
SPS	Failure downtime (SPF)	5E-4		
SPS	Testing and maintenance	9.1E-4		
SPS (alarm system downtime) average value	All	1.2E-3		

Table 8.118: Stairwell Pressurisation System Unavailability

Efficacy

The efficacy of stairwell pressurisation systems is (as discussed) complex and there is no explicit quantification that is suitable for this type of analysis. There is implicit consideration of efficacy issues in the reliability fault tree in that the survey results consider efficacy and reliability rather than pure on demand reliability. The system does depend on the efficacy of the detection system so this will be included in the overall effectiveness. For illustrative purposes it will be assumed the stairwell pressurisation system is operated by a smoke detection system.

Detector Type	Smouldering Fire			Flaming Fire		
	Expected	Lower	Upper	Expected	Lower	Upper
Ionisation	0.1	0.30	0.01	0.05	0.10	0.01
Photoelectric	0.05	0.30	0.01	0.1	0.20	0.01

Table 8.119: Stairwell Pressurisation System Efficacy (Detection System Component)

An example fault tree for a simple stairwell pressurisation system is shown in Figure 8.14.

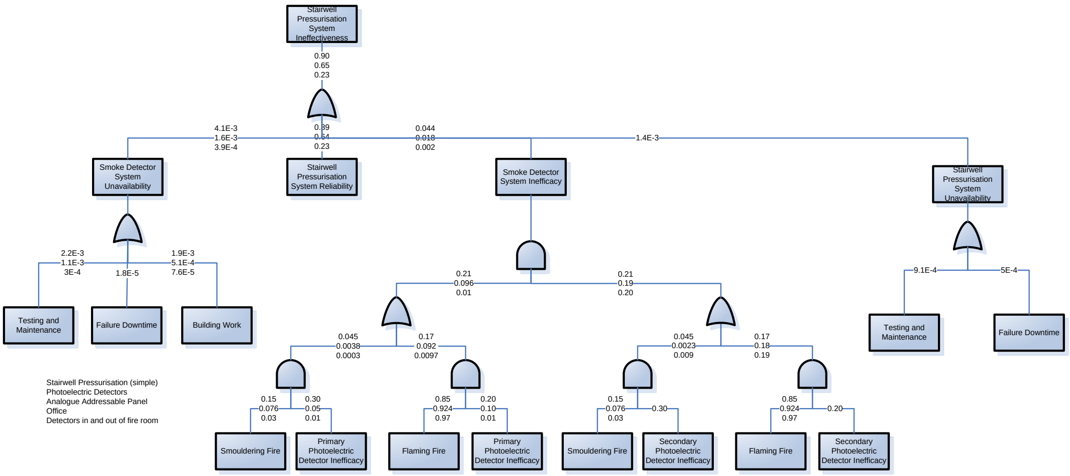


Figure 8.14: Example Fault Tree for Stairwell Pressurisation System Ineffectiveness

Summary results for the nominal effectiveness for a number of typical stairwell pressurisation system design scenarios is shown in Table 8.120.

Design Scenario					**Effectiveness [%]**		
Building	Detectors	Fan	Dampers	Alarm Complexity	Expected	Lower	Upper
Office	Photoelectric	Fixed Speed	Barometric	Simple	35%	10%	77%
	Photoelectric	Variable Speed	Barometric	Simple	27%	6%	73%
	Photoelectric	Variable Speed	Motorised	Simple	30%	7%	74%

Table 8.120: Effectiveness of Stairwell Pressurisation Systems

9

Discussion

System Boundary

The results presented and discussed are for system effectiveness. This is measured (implicitly or explicitly) in terms of system operation as per its design basis. It does not imply a level of life safety. This has to be established by further analysis into tenability and human response.

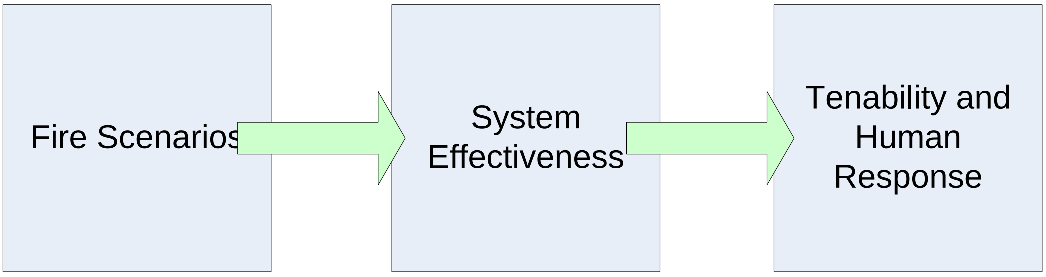


Figure 9.1: Relationship Between System Effectiveness, Fire Scenarios and Human Response

Similarly the effectiveness does not comprehensively account for the range of fire scenarios noting that some attempt has been made to consider the impact of fire characteristics (notably smouldering fires) which have a direct impact on system effectiveness.

Fire Sprinkler Systems

On Demand Reliability

The fault tree predicted on demand reliability of fire sprinkler systems is relatively high. Table 9.1 summarises the on demand reliability for some common system configurations.

Design Scenario			**On Demand Reliability [%]**		
Water Supply	Location	Alarm	Expected	Lower	Upper
Single towns main supply	Auckland	Analogue Addressable	99.2	92	99.8
Diesel Pump and Tank Supply	Any	Analogue Addressable	98.9	77	99.8
Dual supply: Diesel pump and tank; towns main	Auckland	Analogue Addressable	99.4	92	99.9

Table 9.1: On Demand Reliability for a Selection of Typical Fire Sprinkler System Designs

The data used in the fault trees is a combination of reliability data and surveyed industry opinion.

For towns main connected supplies the main contribution to the top level failure probability was failure of the alarm panel, communication systems, interfaces, etc. The remaining contributions were reasonably evenly distributed between the following three groups of fault conditions:

- the water supply (towns main itself),
- the potential for isolation, valve failure or pipe network failure, and
- the potential for sprinklers to fail (not release) due to age, damage or impairment.

With diesel pump and tank supplies, the reliability of the water supply dominates. The lower range (77%) reflects the reduced reliability when maintenance procedures are poor. This rate of failure is not observed in practice as this would require survey of a population of very poorly maintained diesel pumps, it does however reflect a lower bound. The fault tree predicts the diesel pump supply to be slightly less reliable than the town main supply. It must be noted that the analysis has not considered the impact of earthquake. In the event of an earthquake a compliant tank and diesel pump installation would be more likely to be available than the towns main supply. In areas of significant earthquake hazard it is therefore likely that (all other things being equal) the diesel pump and tank would represent a more reliable source of water than a town main supply.

A dual supply has a marginally higher overall reliability than a single supply. This is primarily because the panel failure then dominates the on demand reliability of the system. If it is accepted that the panel failure is not critical[44] then the expected on demand reliability for a dual supply is greater than 99.95% which is consistent with sources such as Marryatt.

These reliabilities in isolation do not accurately reflect the likelihood of effective sprinkler system operation and any such reliability values should be used with caution. If they are used it is recommended that:

- The assumptions used to derive the individual distributions making up the fault tree be considered for applicability to the problem of interest.
- Impact of system availability and efficacy is also included either in a fault tree or event tree type analysis.
- If individual values are used rather than distributions then a sensitivity analysis be undertaken.

The analysis assumes systems designed and installed to NZS 4541. The expected level also assumes typical quality of installation, testing and commissioning. The upper level assumes a higher quality level of installation, testing and commissioning. This will occur by natural variation with differing competencies of people involved in the process, etc. It cannot be assumed to be the expected condition without justification. Even in a well defined and robust approvals environment such as is currently the case in New Zealand there is variation in quality.

The lower level is largely dependent on the quality of maintenance. If systems are poorly maintained reliability levels will trend toward this lower limit. Some current systems may have poor maintenance regimes and will have reliability tending to this lower limit. It is expected that the majority will have typical levels of maintenance consistent with the expected values used in the fault tree analysis.

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[44] This may be appropriate if the sprinkler system panel is not the primary evacuation panel for the building. It is also the view for property protection where panel operation is secondary to discharging water onto the fire.

Predicted reliability is substantially lower than the often claimed reliability for NZ sprinkler systems of 99.5% (less reliable by a factor of 3 to 5), this level of reliability is only reached at the lower limit with favourable values taken through the fault tree. Lower bound reliabilities can be low (approximately 75%) which is predominantly due to poor maintenance and consequence low reliability of diesel pump water supplies. Predictions for town main supplies are for higher levels of reliability though this does not factor in the potential impact of declining town main pressure.

Expected effectiveness is high due in part to installation and commissioning quality and in part to design approaches which increase reliability notably isolation valve monitoring.

Availability

The availability for sprinkler systems is summarised in Table 9.2 for some typical design arrangements. Both the unavailability and the availability values are given. The latter are the values in brackets given as percentages.

System	Cause of Downtime	Expected	Lower	Upper
Sprinkler System (TM connected)	Testing and Maintenance	6.6E-4 (99.93%)	1.3E-2 (98.70%)	2E-4 (99.98%)
Sprinkler System (TM connected)	Failure downtime	1.1E-4 (99.99%)		
Sprinkler System (Diesel pump)	Testing and Maintenance	1.1E-3 (99.89%)	2.2E-3 (99.78%)	6.4E-4 (99.94%)
Sprinkler System (Diesel pump)	Failure downtime	1.5E-4 (99.99%)		
Sprinkler (in office)	Building Work	9.6E-4 (99.90%)	3.7E-3 (99.63%)	1.8E-4 (99.98%)
Sprinkler (in apartment)	Building Work	1.5E-5 (>99.99%)		

Table 9.2: Availability for Sprinkler Systems Typical Values

In general testing and maintenance is the dominant factor with failure downtime being less significant. The values for both are comparable which suggests (on face value) an appropriate balance between maintenance effort and failure downtime.

Tenancy alteration work on high rise office buildings increases the downtime in this occupancy, and for a towns main connected system the isolation time for this may be more significant than the other causes of system unavailability.

There is significant uncertainty in the values for failure downtime and building work and only an expected value is given. Bounds should be determined on a project basis to ensure that the assumptions are appropriate.

The combination of on-demand reliability and availability gives an overall measure of the ability of the system to respond as required. This is summarised below for the expected values for the design cases considered.

Design Scenario			**On Demand Reliability + Availability [%]**
Water Supply	Location	Alarm	Expected
Single towns main supply	Auckland	Analogue Addressable	99.0
Diesel Pump and Tank Supply	Any	Analogue Addressable	98.7
Dual supply: Diesel pump and tank; towns main	Auckland	Analogue Addressable	99.2

Table 9.3: On Demand Reliability plus Availability for a Selection of Typical Fire Sprinkler System Designs

This overall measure is consistent with measures reported by many authors notably DOE, Maybee, Powers and Marryatt. These were studies undertaken in commercial occupancies where arguably on demand reliability and availability are critical and arguably system efficacy is less of an issue. They represent the higher end of published reliability for sprinkler systems.

Efficacy

The efficacy is a significant factor for sprinkler system effectiveness for life safety and for many situations will be more important than the system reliability or system availability.

By its nature efficacy is fire scenario dependent. To enable efficacy to be included in the fault tree analysis three design fire variables have been considered:

Whether the fire is smouldering or flaming
Whether the fire is shielded or unshielded
Whether the fire is in an unprotected concealed space or not.

Simple assumptions have been used to incorporate these factors into the fault tree. These assumptions are expected to be appropriate for many cases but should be examined on a project basis.

There are two key ways in which the efficacy data can be incorporated into the analysis:

Section 1. A fault tree approach can be used with the suggested efficacy values or amended values to reflect the design (and fire scenarios) being considered. This results in an overall effectiveness measure or distribution for the fire sprinkler system which can then be used (for example) as the branch likelihood value in an event tree analysis.

Section 2. An event tree approach can be used where the efficacy factor is explicitly considered in the event tree and the system effectiveness is then conditional upon the event. For example if smouldering fire is the event in the tree then on the ‘yes’ branch the fire sprinkler effectiveness will be much different to the ‘no’ branch, this can be reflected in the system success probabilities and consequence measures.

Assumed inefficacy values due to smouldering fires are highest in residential occupancies due to assumed failure of sprinkler system for any smouldering fire scenario. In office environments it has been assumed that a proportion of smouldering fires will transition to flaming fires prior to critical tenability limits being reached. In an office environment as opposed to a sleeping occupancy there are three smouldering fire outcomes which could be considered:

- Fire never threatens tenability due to low production rate of heat, etc., relative to occupied space.
- Fire transitions to flaming fire and is detected
- Fire does not transition to flaming fire but compromises tenability prior to operation.

Effectiveness

The overall effectiveness has been calculated by combining the effects of reliability, availability and efficacy.

The overall effectiveness is the likelihood that the system will operate as designed. This value (or distribution) is a function primarily of the system design, the building use, and the fire scenario.

There has been some attempt to consider critical aspects of fire scenarios in considering the efficacy but this is not necessarily sufficient. It would be expected that event trees be used to identify specific fire scenarios which may alter the effectiveness of the systems and hence the risk.

For the design scenarios considered the expected effectiveness was approximately 90% for apartment type occupancies and 95% for office type occupancies. The difference between the two being primarily due to the efficacy with smouldering fire scenarios. The upper bound for office occupancies was >99% and for apartments it was approximately 96%. The larger residual with apartments being due the significant number of smouldering fire scenarios for which the system might be expected to be ineffective even with the most favourable factors. The lower bound reflected (primarily) the impact of poor maintenance practices in combination with a high proportion of smouldering fire events and represents the worst case combination of factors.

The expected effectiveness results for the office design cases are consistent with values derived from the Warrington Delphi group and also in the Australian Fire Engineering Guidelines for flaming fires. They are also consistent with the range indicated by the Automatic Sprinkler study, and with values reported by Miller, Power, Richardson, Finucane, sprinkler focus and Milne.

The effectiveness level for apartments is broadly consistent with value reported by BRE.

If smouldering fire events are excluded from the analysis the expected effectiveness levels are approximately 98% to 98.5% for offices and apartments. This then is consistent with values reported by DOE, Maybee, Powers and Marryatt. This perhaps reflects that these values are based upon data from well maintained and managed premises with infrequent smouldering fires (or where non response to smouldering fire is not considered a system failure).

For design purposes it is considered that as a first order approximation the following system effectiveness values be used for NZS 4541 sprinkler systems:

- Apartment sprinkler system - 90%
- Office sprinkler system - 95%

Distributions of values are dependent on design, particularly water supply arrangements. The following table presents distributions for selected design options. Other design options can be developed following the approaches in the report.

Design Scenario				**Effectiveness [%]**		
Water Supply	Location	Alarm	Occupancy	Expected	Lower	Upper
Single towns main supply	Auckland	Analogue Addressable	Apartment	90%	59%	96.6%
			Office	95.6%	81%	99.4%
Diesel Pump and Tank Supply	Any		Apartment	90%	46%	96.5%
			Office	95.3%	67%	99.3%
Dual supply: Diesel pump and tank; towns main	Auckland		Apartment	90%	61%	96.6%
			Office	95.9%	89%	99.5%

Table 9.4: Sprinkler System Effectiveness

Heat Detection Systems

On Demand Reliability

As would be expected on demand reliability is somewhat lower than for sprinkler systems. Expected reliability typically around 98% for simple systems but reliability declining rapidly with highly complex systems where expected on demand reliability is approximately 90%. This is primarily due to potential issues with panel programming as well as hardware faults. Anecdotal evidence is that maintenance activities on panels can create problems where maintenance technician is not fully aware of panel configuration. The simple case and the complex case represent an upper and lower bound and for many projects the on demand reliability (or distribution) would fall between these two. The failure rate for software at the panel is not well understood and the value is subject to considerable uncertainty as it is heavily reliant on opinion from industry rather than published values. It is expected to be conservative for the majority of cases.

Availability

The availability of heat detection systems is comparable to sprinkler systems and given the somewhat lower on demand reliability of heat detection the relative importance of availability is less than for sprinkler systems. The overwhelming reason for lack of availability is testing and maintenance on the system.

Efficacy

Efficacy considerations are similar to those for sprinklers and the same basic analysis and assumptions have been used.

Effectiveness

As for sprinkler systems effectiveness of heat detection systems are lower in apartments due to the greater impact of smouldering fire scenarios on efficacy. For simple systems the expected effectiveness is approximately 95% for office occupancies and approximately 90% for apartment occupancies. For highly complex systems the effectiveness drops to approximately 85% for office systems and 80% for apartment systems.

The 90% value is consistent with design values used in the Fire Engineering Design Guidelines.

For design purposes it is considered that as a first order approximation the following system effectiveness values be used for NZS 4512 heat detection systems:

- Simple office heat detection system - 95%
- Simple apartment heat detection system - 90%
- Complex office heat detection system - 85%
- Complex apartment heat detection system - 80%

Distributions of values are dependent on design, particularly complexity of the system. The following table presents distributions for selected design options. Other design options can be developed following the approaches in the report.

Design Scenario		Effectiveness [%]		
Design	Location	Expected	Lower	Upper
Simple Alarm	Office	94.4%	81%	99.5%
Simple Alarm	Apartment	88.8%	59%	96.0%
Complex Alarm	Office	84%	58%	98.8%
Complex Alarm	Apartment	79%	38%	96.0%

Table 9.5: Heat Detection System Effectiveness

Smoke Detection Systems

On Demand Reliability

On demand reliability predicted through the fault tree is similar to that for heat detection. As for heat detection two design approaches were considered a simple system and complex system. As with heat detection these represent bounding cases of the simplest and most complex credible systems with expected on demand reliability of approximately 98% and 90% respectively. Although there was some data on relative reliability of ionisation and photoelectric detectors this was limited and was not used as a basis for differentiation.

Availability

The availability of the smoke detection system is comparable with heat detection systems and as for heat detection systems the availability has less impact than on demand reliability on the overall effectiveness of the system. There was no data suggesting different availabilities of photoelectric and ionisation detectors. Given the maintenance and testing requirements are the same and the failure rates are similar it would be expected that there is no significant difference.

Efficacy

As for sprinklers and heat detectors the fire type has an impact on the system efficacy. The results are different for different detector types and values are presented for photoelectric and ionisation detectors. Expected efficacy levels in smouldering fires are relatively high at 70% to 90% for ionisation detectors and 70% to 95% for photoelectric detectors. Relative efficacy is higher for ionisation detectors for flaming fires and higher in general than the response to smouldering fires. These values are based upon a range of experimental data including the work by Ahrens. Some research predicted lower efficacy levels but many of the fire scenarios are extremely challenging and intended to differentiate between detectors rather than demonstrate efficacy in realistic fire scenarios. The range selected is a compromise between the various values.

As with sprinklers and heat detection efficacy dominates the overall effectiveness particularly because of the potential for non detection of smouldering fires. This is to a lesser extent than sprinklers and heat detectors since smoke detectors are of course able to detect these fire types with some reliability.

Effectiveness

Effectiveness of smoke detection systems is dominated by efficacy. This is typically 2 to 4 times more significant in the overall effectiveness than on demand reliability, which is itself more important than availability.

The highest effectiveness is seen in open plan office type environments which have expected effectiveness levels of approximately 96% to 97%. With highly complex systems this effectiveness could decrease markedly to 86% to 87%.

Effectiveness is comparable in offices to open plan residential layouts where there is confidence that multiple detectors will be effectively exposed to the results of a fire.

A more realistic scenario for residential apartments is a highly divided layout where there is a significant potential for a fire exposing only one or two detectors, an example being a fire in a closed bedroom. In this situation assumptions made regarding efficacy result in a reduced effectiveness of approximately 88% (photoelectric) to 93% (ionisation) for the simple system case and approximately 78% (photoelectric) to 82% (ionisation) for the highly complex system case. Ionisation detectors are predicted as more reliable as they are assumed to perform slightly more reliably for flaming fires and flaming fires are more common than smouldering fires.

The reliability levels from the fault trees are consistent with design values which are typically in the range 80% to 90%.

For design purposes it is considered that as a first order approximation the following system effectiveness values be used for NZS 4512 smoke detection systems:

Simple office smoke detection system -	96% (photoelectric); 97% (ionisation)
Simple apartment smoke detection system -	88% (photoelectric); 93% (ionisation)
Complex office smoke detection system -	86% (photoelectric); 87% (ionisation)
Complex apartment smoke detection system -	78% (photoelectric); 82% (ionisation)

(Noting that this is only effectiveness in terms of operation as per design not a reflection on the life safety performance).

Distributions of values are dependent on design, particularly complexity of the system. The following table presents distributions for selected design options. Other design options can be developed following the approaches in the report.

Design Scenario				**Effectiveness [%]**		
Building Type	Detectors	Design	Open Plan	Expected	Lower	Upper
Apartment	Photoelectric	Simple	No	88%	69%	98.2%
	Ionisation	Simple	No	92.6%	78%	98.2%
	Photoelectric	Complex	No	78%	46%	99%
	Ionisation	Complex	No	82%	53%	99%
	Photoelectric	Simple	Yes	96.2%	86%	99%
	Ionisation	Simple	Yes	97.5%	89%	99%
	Photoelectric	Complex	Yes	86%	63%	99%
	Ionisation	Complex	Yes	87%	67%	99%
Office	Photoelectric	Simple	Yes	96.2%	86%	99%
	Ionisation	Simple	Yes	97.5%	89%	99%
	Photoelectric	Complex	Yes	86%	63%	99%
	Ionisation	Complex	Yes	87%	67%	99%

Table 9.6: Smoke Detection System Effectiveness

Stairwell Pressurisation Systems

On Demand Reliability

Considered across the system as a whole expected reliability levels are low. For the design arrangements examined the reliability ranged from 28% to 36%. The main contribution to the lack of reliability was the building construction and door hardware. This values used for these factors were based solely on Fazio amended by NZ survey data and there is significant uncertainty in these values. If the contribution from these factors is removed the expected reliability increases to between 47% to 60%.

It could be considered that there are four distinct populations of systems:

- Case 1: Those which have been well designed and independently commissioned and are well tested and maintained;
- Case 2: Those which have been well designed and independently commissioned and are not well tested and maintained;
- Case 3: Those where design and commissioning is uncertain but they are well tested and maintained.
- Case 4: Those where design and commissioning is uncertain but they are not well tested and maintained

The reliability of case 1 would be expected to be at the upper limits (including management of construction aspects). For case 2 it would be expected that reliability would be lower maybe around expected levels (Including possible construction faults being introduced). For case 3 the lack of commissioning would increase risk of failure but maintenance would somewhat correct this and reliability around expected levels is suggested. For case 4 the reliability would be at lowest levels. Summarising this for the various design types:

Design Scenario	**Reliability [%]**			
	Case 1	Case 2	Case 3	Case 4
Fixed speed fan and barometric dampers	84%	36%	60%	11%
Variable Speed drive system	80%	28%	47%	6%
Variable Speed drive and motorised damper system	82%	31%	52%	7%

Table 9.7: Reliability of Stairwell Pressurisation Systems for Various Commissioning, Testing and Maintenance Scenarios

An overall estimate of reliability can be approximated by considering the proportions of each case. There is little data available on this but a value will be calculated for illustrative purposes. Industry estimates are that approximately 60% of systems are independently commissioned. If it is assumed that of these 80% are well tested, and that of the systems that are not independently certified only 20% are well tested this gives use the following breakdown:

Commissioning, Testing & Maintenance Scenario	**Proportion of Installations**
Case 1	48%
Case 2	12%
Case 3	8%
Case 4	32%

Table 9.8: Estimated Proportions (Nominal) of Each Commissioning, Testing and Maintenance Scenario

The overall reliabilities based on this nominal distribution are then:

Design Scenario	Reliability [%]
Fixed speed fan and barometric dampers	52%
Variable Speed drive system	47%
Variable Speed drive and motorised damper system	49%

Table 9.9: Estimated Overall Reliabilities for Stairwell Pressurisation Systems

Unavailability

System unavailability is a combination of the pressurisation system availability and the alarm system availability. Contributions from each of these is approximately equal and together the account for 0.26% of unavailability which is minor compared to the levels of unreliability.

Efficacy

The efficacy of stairwell pressurisation systems is (as discussed) complex and there is no explicit quantification that is suitable for this type of analysis. There is implicit consideration of efficacy issues in the reliability fault tree. The detection system does depend on the efficacy of the detection system so this will be included in the overall effectiveness. For illustrative purposes it will be assumed the stairwell pressurisation system is operated by a smoke detection system. In this case the expected efficacy is approximately 95%.

Effectivess

The overall effectiveness level would be expected to be in the 40% to 60% range dependent on the make-up of the population of systems. This value is consistent with Zhao who estimated reliability levels of 52% to 62%. Moran surveyed systems and found 66% reliability. Fazio predicted levels of reliability consistent with the lower effectiveness levels.

For design purposes it is suggested that a specific analysis be undertaken based on the system design. If this is not practical for a first order estimate the following point values are suggested:

Design Scenario	Effectiveness [%]
Fixed speed fan and barometric dampers	52%
Variable Speed drive system	47%
Variable Speed drive and motorised damper system	49%

Table 9.10: Approximate Design Values for Stairwell Pressurisation System Effectiveness

These values will be conservative for an independently commissioned system and may be adjusted using engineering judgement.

Distributions of values are dependent on design, particularly complexity of the system. The following table presents distributions for selected design options. Other design options can be developed following the approaches in the report.

Design Scenario	Reliability [%]			
	Case 1	Case 2	Case 3	Case 4
Fixed speed fan and barometric dampers	84%	36%	60%	11%
Variable Speed drive system	80%	28%	47%	6%
Variable Speed drive and motorised damper system	82%	31%	52%	7%

Table 9.11: Approximate Ranges Design Values for Stairwell Pressurisation System Effectiveness for Various Levels of Commissioning, Testing and Maintenance

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Conclusions

The effectiveness for selected fire protection systems was analysed using fault tree methods. The underlying data was from a combination of sources including reliability data, fire industry statistics, fire brigade statistics, specific research projects, expert judgement and surveys of the New Zealand fire protection industry.

The effectiveness measures obtained were specific to the system designs analysed. Designs were considered for two building types, multi-storey apartments and multi-storey office buildings. For each building type common design alternatives were assessed for example using differing water supply arrangements for sprinklers, different detectors for alarm systems, and different fan and damper arrangements for stairwell pressurisation systems. Significant variation in effectiveness were found between design types. For sprinkler systems the expected effectiveness values ranged between 90% and 96%. For alarm systems the expected effectiveness ranged between 86% and 97%. For stairwell pressurisation systems the effectiveness varied between 26% to 38% (or 47% to 60% if construction faults were excluded).

The expected effectiveness ranges are generally consistent with design values published in the literature and values reported from incident data.

Values for sprinkler system effectiveness are lower than reported by Marryatt. In part this can be accounted for by the fact that the effectiveness of sprinkler systems is highly dependent on the fire scenario. In the effectiveness analysis a significant proportion of smouldering fires have been included for which the sprinkler system efficacy is very low. This lowers the overall effectiveness measure for the sprinkler system and is appropriate when determining the effectiveness of these systems as the basis for design. The Marryatt data firstly is not presented as a design value in the sense that is being reported here and secondly would not be expected to include a large number of smouldering fire scenarios as these would either be unreported or if reported may be categorised as too small to operate the system and hence not be regarded as system failures. The on demand reliability plus availability predicted by the fault trees was in the range 98.7% to 99.2%. This is closer to the value from Marryatt and reflects the effectiveness of systems where there is a negligible risk associated with smouldering fires such as may be expected in many industrial and storage occupancies. The remaining gap between these values and Marryatt is presumed to be due to the significant proportion of reliability failures resulting from panel faults. Since panel faults have an impact on life safety they are considered critical system failures. If panel faults are not seen as critical failures which would be a position which could be taken for property protection then the expected reliability increases to between 99.4% and 99.8%.

For each system an efficacy distribution has been determined based upon simply taking the upper and lower bounds for each component part of the fault tree. The resulting upper and lower bounds represent extreme cases of all factors favourable or all factors unfavourable. The bounds for a sprinkler system range from less than 50% effectiveness to greater than 99% effectiveness. The lower bound is mainly due to a combination of reduced reliability as a result of poor (extended period) maintenance and reduced efficacy as a result of an assumed higher proportion of smouldering fires. Designs reliant on a diesel pump supply are particularly prone to a marked decrease in reliability due to testing and maintenance, towns main supplies appear to be more resilient.

The range in the expected value for the alarm system effectiveness is due in part to the type of building. The efficacy is somewhat higher for office type occupancies due to the reduced sensitivity to smouldering fires; it is also a reflection of the complexity of the alarm system and to a lesser extent the type of detector. The high effectiveness values are for office occupancies with simple systems and ionisation smoke detection.

As for sprinkler systems the upper and lower bound for the effectiveness is determined by taking the upper and lower bound for each part of the fault tree. The range across all design options is from 46% to 99%. As for sprinklers the lower bound is in part due reduced efficacy for smouldering fires and in part due to reduced liability due to poor maintenance. Maintenance has a proportionally greater impact on complex alarm systems compared to simple systems and has a more significant impact than maintenance of town main sprinkler systems.

The range in the expected value for the stairwell pressurisation system effectiveness is dependent primarily on the system design. The more effective systems being the simpler designs. The effective range is consistent with design values and research values.

The range across all options including lower and upper bound is 6% to 84%. The range is so wide because of the uncertainty in the reliability of the system components and is indicative of the sensitivity of the effectiveness of stairwell pressurisation systems to the quality of commissioning, testing and maintenance.

Generic design values for effectiveness have been established from the analysis both as point (expected) values and also distributions with lower and upper bounds. The point values are reproduced here for convenience.

Design Scenario	**Effectiveness [%]**
Sprinkler System Office Building	95%
Sprinkler System Apartment Building	90%
Simple office heat detection system	95%
Simple apartment heat detection system	90%
Complex office heat detection system	85%
Complex apartment heat detection system	80%
Simple office smoke (photoelectric) detection system	96%
Simple apartment smoke (photoelectric)detection system	88%
Complex office smoke (photoelectric)detection system	86%
Complex apartment smoke (photoelectric)detection system	78%
Simple office smoke (ionisation) detection system	97%
Simple apartment smoke (ionisation)detection system	93%
Complex office smoke (ionisation)detection system	87%
Complex apartment smoke (ionisation)detection system	82%
Fixed speed fan and barometric dampers	52%
Variable Speed drive system	47%
Variable Speed drive and motorised damper system	49%

Table 10.1 Fire Protection Systems Nominal Expected Effectiveness

These values are expected values and may not be conservative for a specific design application. The variation in effectiveness of systems with changes to design basis indicates care needs to be taken in the use of generic effectiveness values. This is an issue both for absolute analysis where the uncertainty may lead to an inappropriate estimate of the level of risk and for comparative analysis where the (potential) differing sensitivity of design options to the underlying assumptions may lead to erroneous conclusion. For design purposes conservative selection of effectiveness values can compensate for knowledge uncertainty in the former case but not for comparative analysis.

The level of uncertainty can be reduced by ensuring that the analysis is specific to the design. By adaptation of the fault trees or by the use of combined fault tree and event tree analysis.

Quantification of the uncertainty can be achieved by using a discrete sensitivity analysis or a probabilistic type analysis.

For sprinkler systems and alarm systems efficacy of the design for the design fires is a key consideration and for a number of scenarios the system efficacy will be the dominant factor in the overall effectiveness. Reliability is sensitive to maintenance frequency (and quality) and a decline in the level of maintenance has a marked impact on the level of reliability. Reliability of the system can then become the dominant factor in the effectiveness of the system. Current testing and maintenance regimes for sprinklers and alarms in New Zealand are relatively robust (though not without opportunity for improvement). There are a number of changes (positive and negative) which may impact on the effectiveness of these systems.

Trend or Change	Systems Affected	Likely Result
Changes in Building Regulation	All, but particularly alarms	Positive, increase in focus on construction monitoring, quality of documentation and ongoing testing.
Changes in Sprinkler Certification	Sprinklers	Negative, increase variation in Standards.
Increased numbers of systems to NZBC	Sprinklers	Negative, increased risk of failure due to exposure fire or water supply failure.[45]
Back Flow Prevention	Sprinklers	Negative, increased risk of system isolation.
Municipal water supply pressure reduction	Sprinklers	Negative, increased risk of failure under challenging conditions.
Increasing System Complexity	Particularly alarms	Negative, increased risk of design, installation or maintenance error.
		Positive, better diagnostics, decreased false alarm performance, better accuracy.

Table 10.2: Impact of Changes and Trends on Sprinkler and Alarm System Effectiveness

For stairwell pressurisation systems the reliability of the system is the key in terms of system effectiveness. Reliability is highly sensitive to the quality of commissioning and maintenance. Industry opinion is that current levels of commissioning, testing and maintenance fall short of levels where there can be confidence in high levels of stairwell pressurisation system effectiveness. Of the general trends the ones that effect alarms also affect stairwell pressurisation systems are summarised in Table 12.3.

Trend or Change	Systems Affected	Likely Result
Changes in Building Regulation	All	Positive, increase in focus on construction monitoring, quality of documentation and ongoing testing.
Increasing System Complexity	Particularly VSD systems	Negative, increased risk of design, installation or maintenance error.
		Positive, better diagnostics, precision. Lower risk of mechanical failure.

Table 10.3: Impact of Changes and Trends on Stairwell Pressurisation System Effectiveness

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[45] The exposure fire hazard is difficult to quantify. Statistics on exposure fires can be used to identify the prevalence of the initiating event but there is limited data available relating this to system failure.

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Further Work

There are a number of areas which would benefit from further work, these include:

- A detailed analysis of the FPIS dataset to differentiate faults for different occupancy types and to provide better resolution of the fault severity under the code heading. Over time this dataset could provide a basis for examination of trends in fire protection system performance.
- A comprehensive review of stairwell pressurisation system performance based upon site commissioning inspections and test results.
- Extension of the analysis to explicitly include for other occupancies including other sleeping type occupancies as well as crowd occupancies.
- Extension of the analysis to include passive fire protection systems.

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Appendix A

Survey Forms

The form for stairwell pressurisation systems is based upon the work by Fazio.

Sprinkler System Problems

This survey is to support Fire Service research into system reliability for life safety I appreciate any assistance you can give. Please answer all the questions you can.

Out of every one hundred (100) systems surveyed, where the problem could occur[46], how many times have you found the following significant problems? If never seen write never.

Some problems occur less frequently so the value will be less than 1.

e.g. If you have seen systems with impaired towns main supplies twice and you estimate you have surveyed around 1000 systems with towns mains then write in "2 out of 1000" or write in 0.2

Problem	**How often observed (out of 100 surveys) ?**
Water supply isolated (e.g. closed T.M. valve)	
Water supply impaired (e.g. partly shut valve)	
Water supply inadequate for design demand	
Diesel pump won't start (e.g. disconnected umbilical)	
Electric pump won't start	
No monitoring of isolation valves	
Floor isolating valves isolated (unmonitored or monitoring compromised)	
Unprotected ceiling spaces (where arrangement non compliant with 4541).	
Unprotected areas below the ceiling (e.g. new partition creating unprotected office).	
Alarm signalling not operational (no call to brigade)	
Alarm sounders not working	
Sprinklers with cracked bulb	

{Optional} Your name and a contact number and total number of surveys undertaken ?

____

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[46] For example for floor isolation valves based your values on the number of systems surveyed where floor isolation valves are installed.

Please fax back to Neil Gravestock on 09 358 1573.

Alarm System Problems

This brief survey is to support Fire Service research into system reliability for life safety I appreciate any assistance you can give. Please answer all of the seven questions you can.

Out of every one hundred (100) systems surveyed how many times have you found the following significant problems? If never seen write never.

The survey is limited to systems installed to NZS 4512 do not consider domestic type or integrated fire/security type systems.

Problem	**How often observed (out of 100 surveys) ?**
System isolated (due to fault/human error) or without power	
System partly isolated (due to fault/human error)	
Areas without detectors installed (e.g. new rooms or partitioning changes)	
Detectors tampered with (e.g. disconnected or covered)	
Faulty detectors (would not operate in event of fire)	
Wrong detector type used for location (significantly delayed response in event of fire)	
Backup battery power supply not operational	
Alarm signalling not operational (no call to brigade)	
Alarm sounders not working	

What is the typical average system size - number of detectors? _______________

{Optional} Your name and a contact number and total number of surveys undertaken ?

____

Please fax back to Neil Gravestock on 09 358 1573.

Stairwell Pressurisation System Problems

This brief survey is to support Fire Service research into system reliability for life safety I appreciate any assistance you can give. Please answer all of the seven questions you can.

Out of every one hundred (100) systems surveyed how many times have you found the following significant problems? If never seen write never.

The survey is limited to systems installed to AS 1668.1

Fault	**Frequency (out of 100 cases)**
Components	
Wiring/Cabling	
Wiring fault1 associated with..	
FIP (fire indicator panel)	
SPF (stair pressurisation fan)	
MSSB (mechanical services switchboard for SPFs)	
VSD (variable speed drive)	
Smoke/other detector	
Other? (please state)	
Relay fault1 associated with..	
FIP (fire indicator panel)	
SPF (stair pressurisation fan)	
MSSB (mechanical services switchboard for SPFs)	
VSD (variable speed drive)	
Smoke/other detector	
Other? (please state)	
Fault1 with pressure sensor	
Incorrect pressure sensor installed (eg out of range, low pressure sensitivity)	
Blocked tubing	
Electrical malfunction	
Supply voltage applied to output	
Pressure reading not stable, non repetitive(*)	
Calibration shift due to overpressure	
Differential pressure location not established/incorrect	
All of the above	
Other? (please state)	
Total Fault estimate out of 100 cases	
Fault1 with damper	
Damper does not close (more) when required	
Damper does not open (more) when required	
Damper jammed/sticking	
Damper not operational because of actuator fault1	
Damper does not open because installed motor has insufficient torque	
Damper weights need adjusting	
Other?	

SPFs	
SPF does not work because..	
Broken fan blades	
MSSB has isolated the SPF to be off, so fan doesn’t run	
FFCP (fire fan control panel) has overridden the SPF to off/stop, so fan doesn’t run	
Keylock switch (ie isolator switch) at SPF is off, so fan doesn’t run	
Power failure to SPF (note type of power)	
SPS with VSDs and the BSD is fault1 (eg not sending correct signal to SPF, so fan speed’s not correct)	
Slipped fan belts	
SPFs shaft/keyway sheared	
SPFs discharge damper/bypass damper closed (when should be open)	
Other?	
FIPs	
FIP does not work because…	
Microprocessor inside FIP does not work	
FIPs program has changed since commissioning	
No power to FIP	
Other? (please state)	
Damper Motors/Actuators	
Damper/Actuator does not work because…	
Motor runs backwards	
Fuses incorrectly installed	
Incorrect fuses	
Actuator mechanism has not been correctly adjusted	
Other? (please state)	
Fault1 with VSD	
Algorithm mis-programmed/altered in VSD	
Power failure to VSD (note type of power)	
Microprocessor fault1 with VSD	
Relays/contacts not operational in VSD	
VSD faults1 due to high temperature environment	
Other?	
Total fault estimate out of 100 cases	
Fault1 with stairwell doors	
Poorly fitted doors ie rubbing against door frame	
Faulty1 door closure device	
Door forces too high because of external environmental conditions(**)	
Other?	
Total fault estimate out of 100 cases	
Commissioning	

Door forces less than 110N	
Airflow velocity at door greater than 1m/s	
Noise measurement within limits of AS1668.1	
Restoration times within limits of AS1668.1	
Manual fan override controls work	
Other	
Additional holes/leakages in stair shaft	
Pressure too high in stairwell, tight stairwell	
Relief on occupied floors blocked/restricted	
Building itself, is too leaky for SPS	
Total fault estimate out of 100 cases	

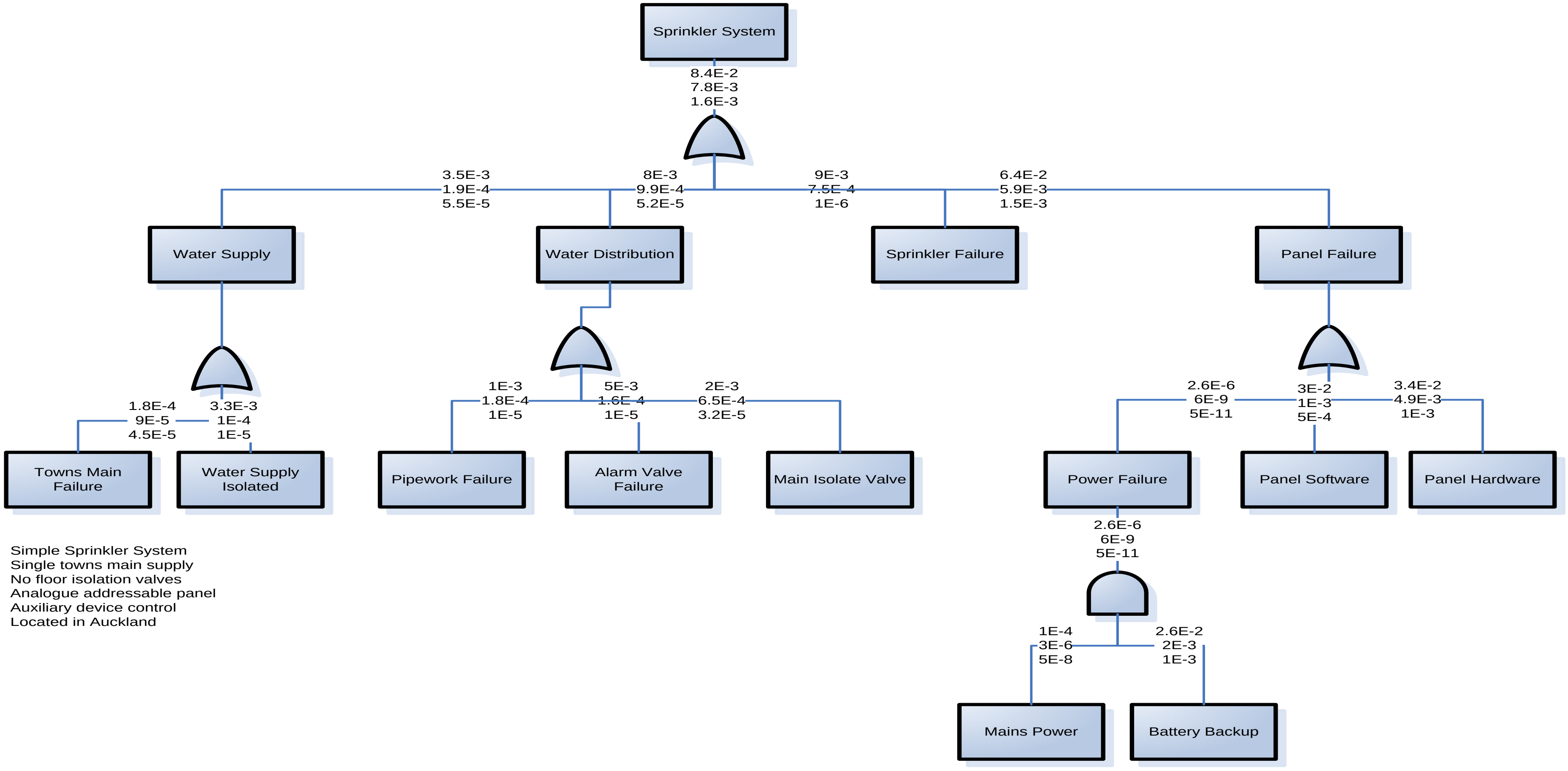
{Optional} Your name and a contact number and total number of surveys undertaken ?

____

Please fax back to Neil Gravestock on 09 358 1573.

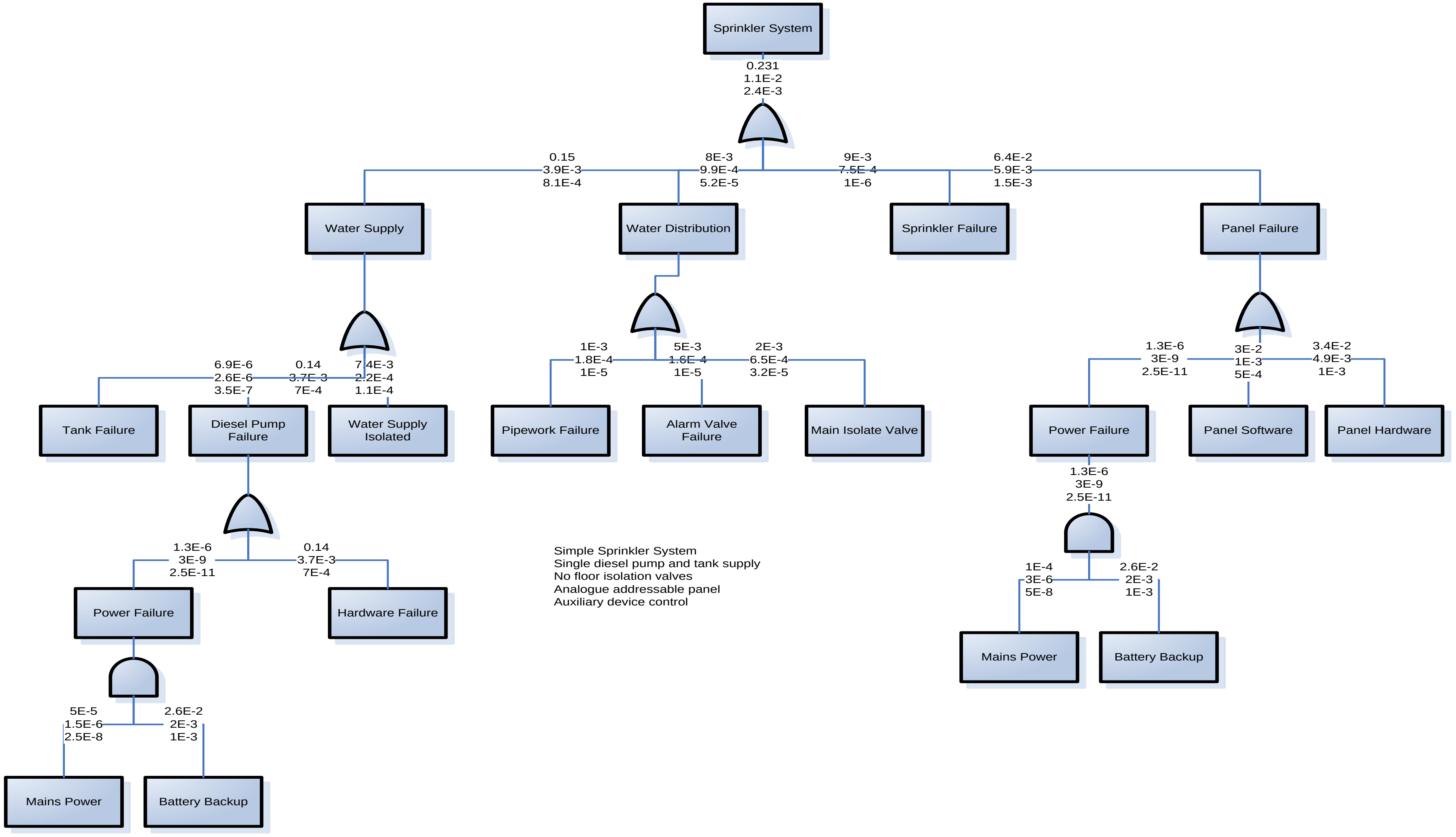
Appendix B

Reliability Fault Tree Examples



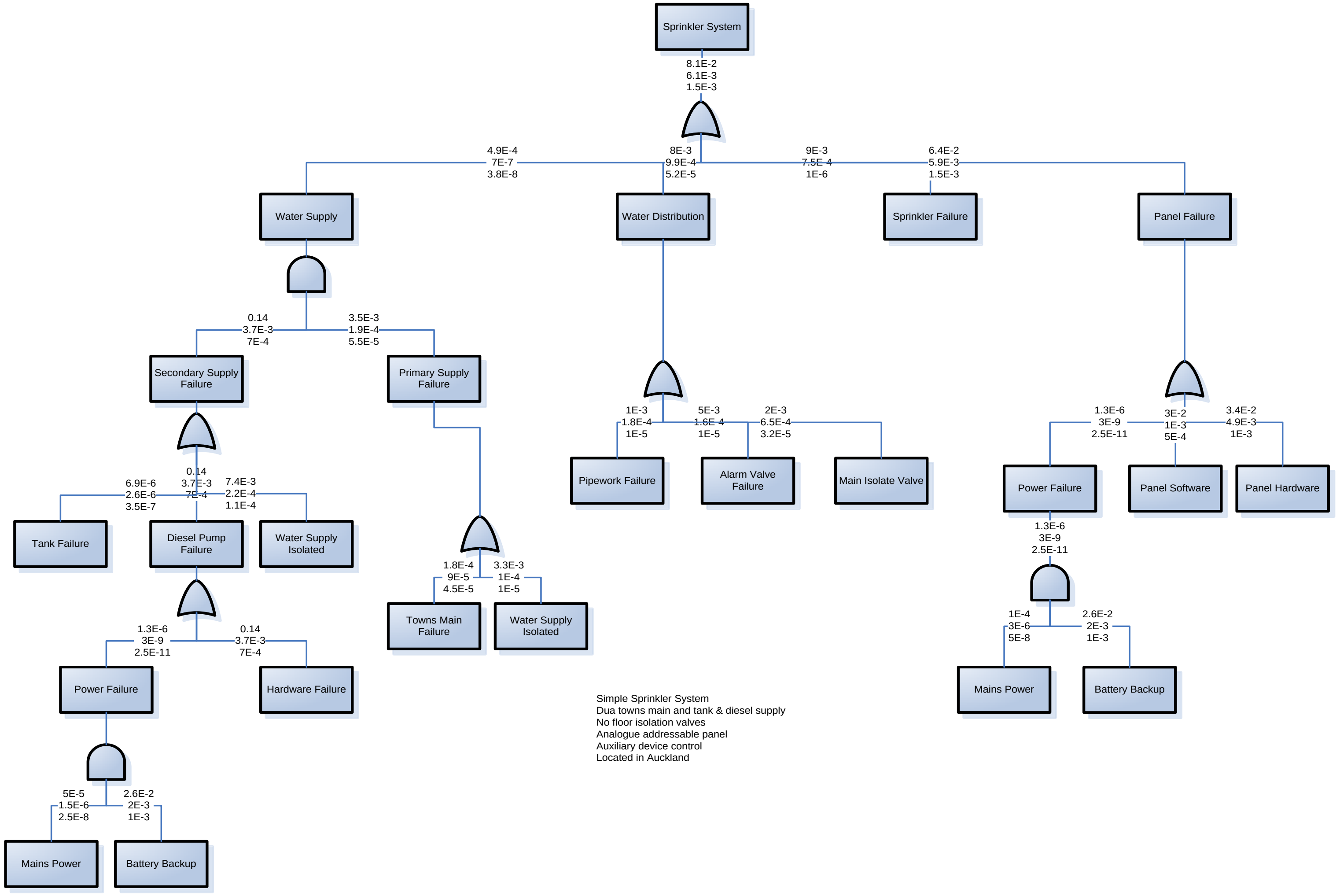
Simple Sprinkler System
Single towns main supply
No floor isolation valves
Analogue addressable panel
Auxiliary device control
Located in Auckland

Figure B.1: Sprinkler System Reliability Fault Tree



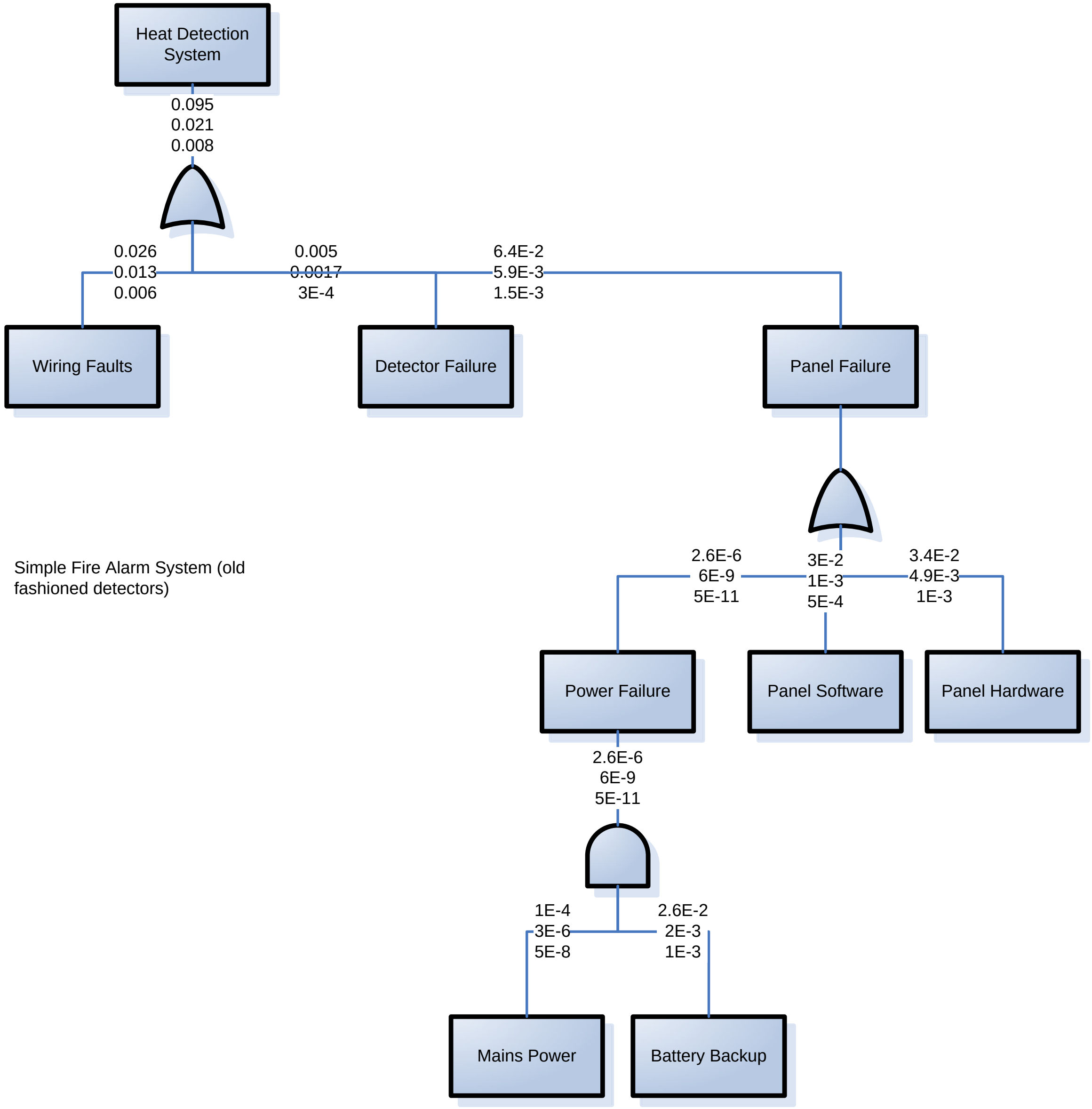
Simple Sprinkler System
Single diesel pump and tank supply
No floor isolation valves
Analogue addressable panel
Auxiliary device control

Figure B.2: Sprinkler System Reliability Fault Tree



Simple Sprinkler System
Dua towns main and tank & diesel supply
No floor isolation valves
Analogue addressable panel
Auxiliary device control
Located in Auckland

Figure B.3: Sprinkler System Reliability Fault Tree



Simple Fire Alarm System (old fashioned detectors)

Figure B.4: Heat Detection System Reliability Fault Tree

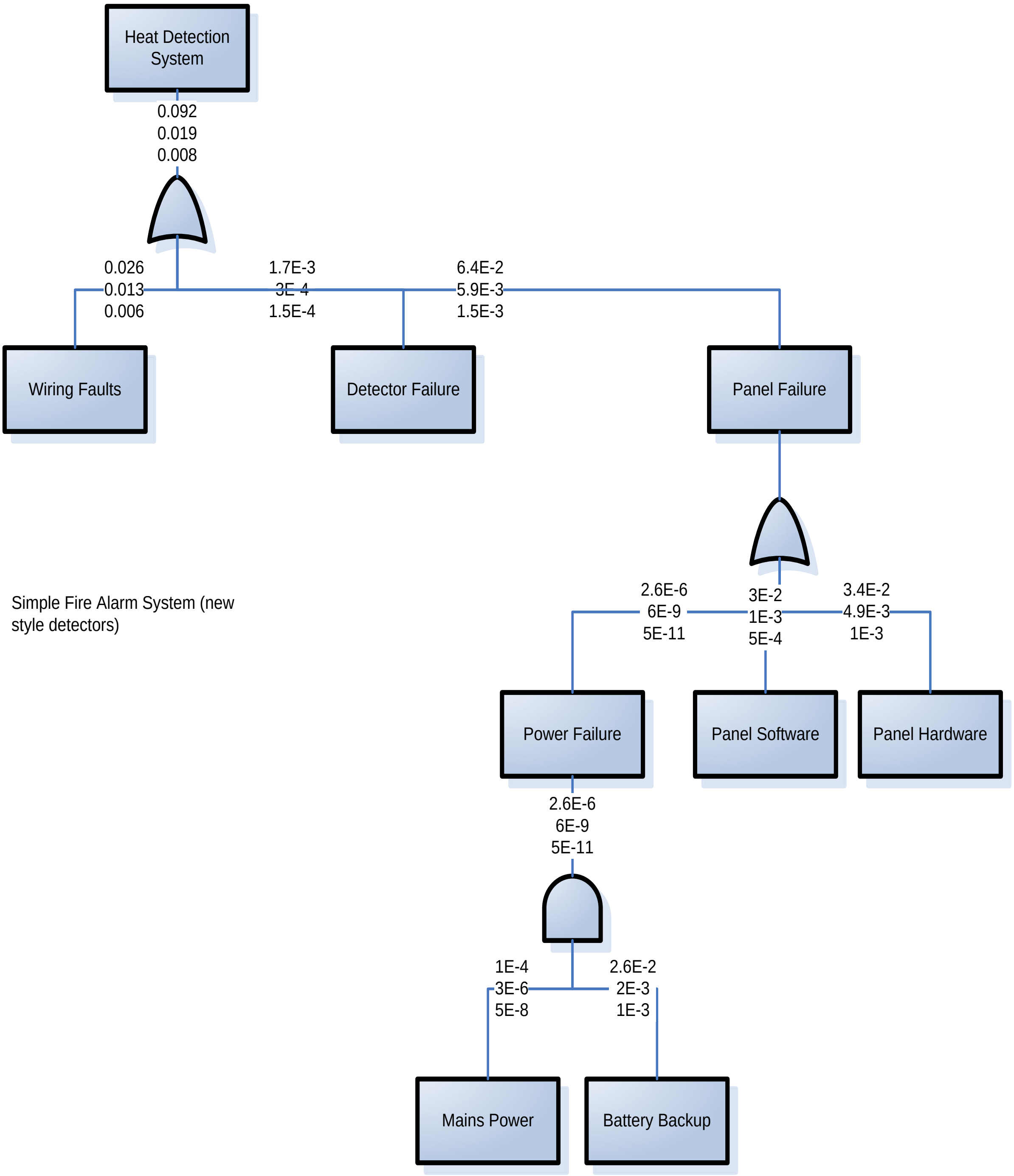


Figure B.5: Heat Detection System Reliability Fault Tree

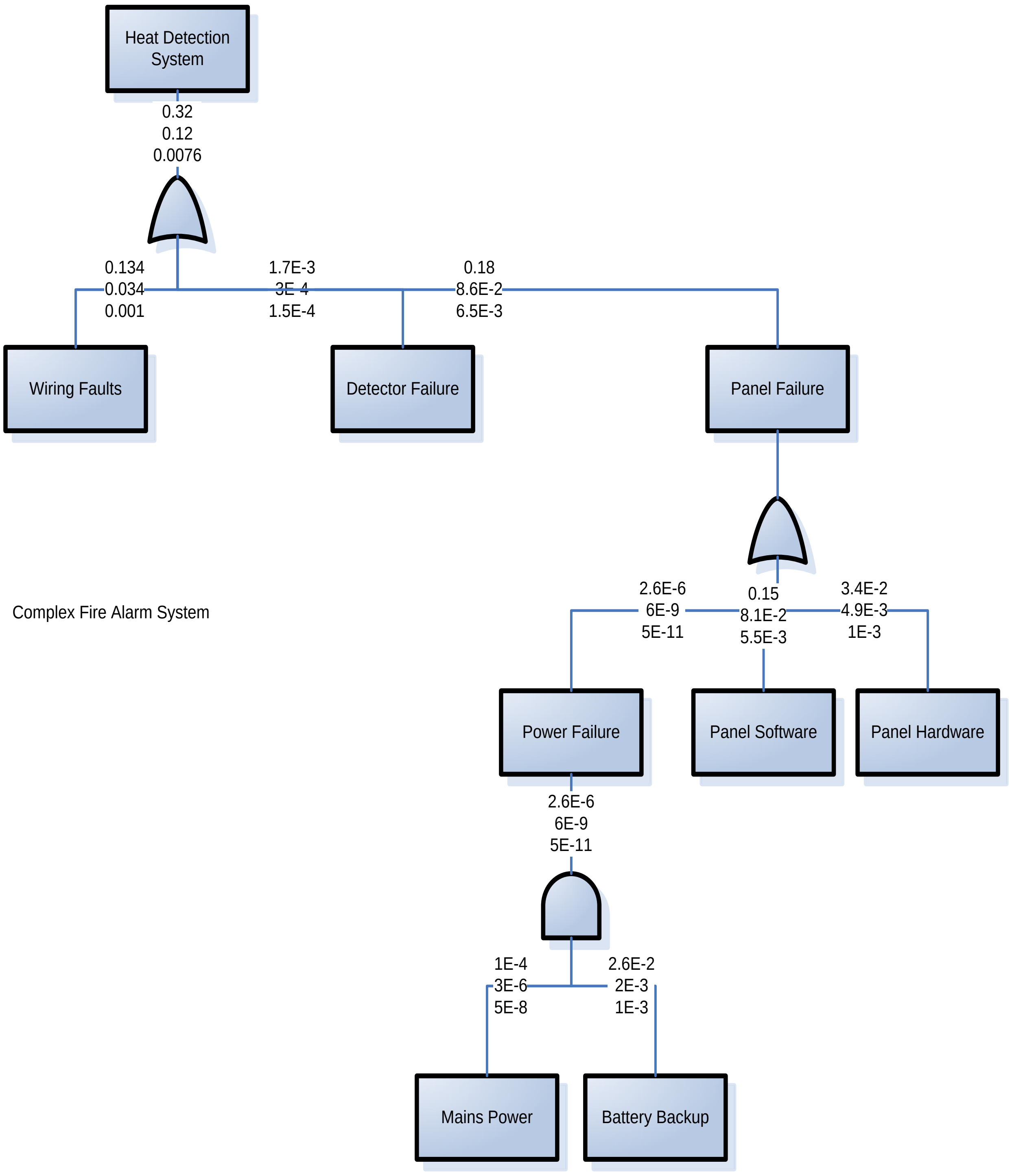


Figure B.6: Heat Detection System Reliability Fault Tree

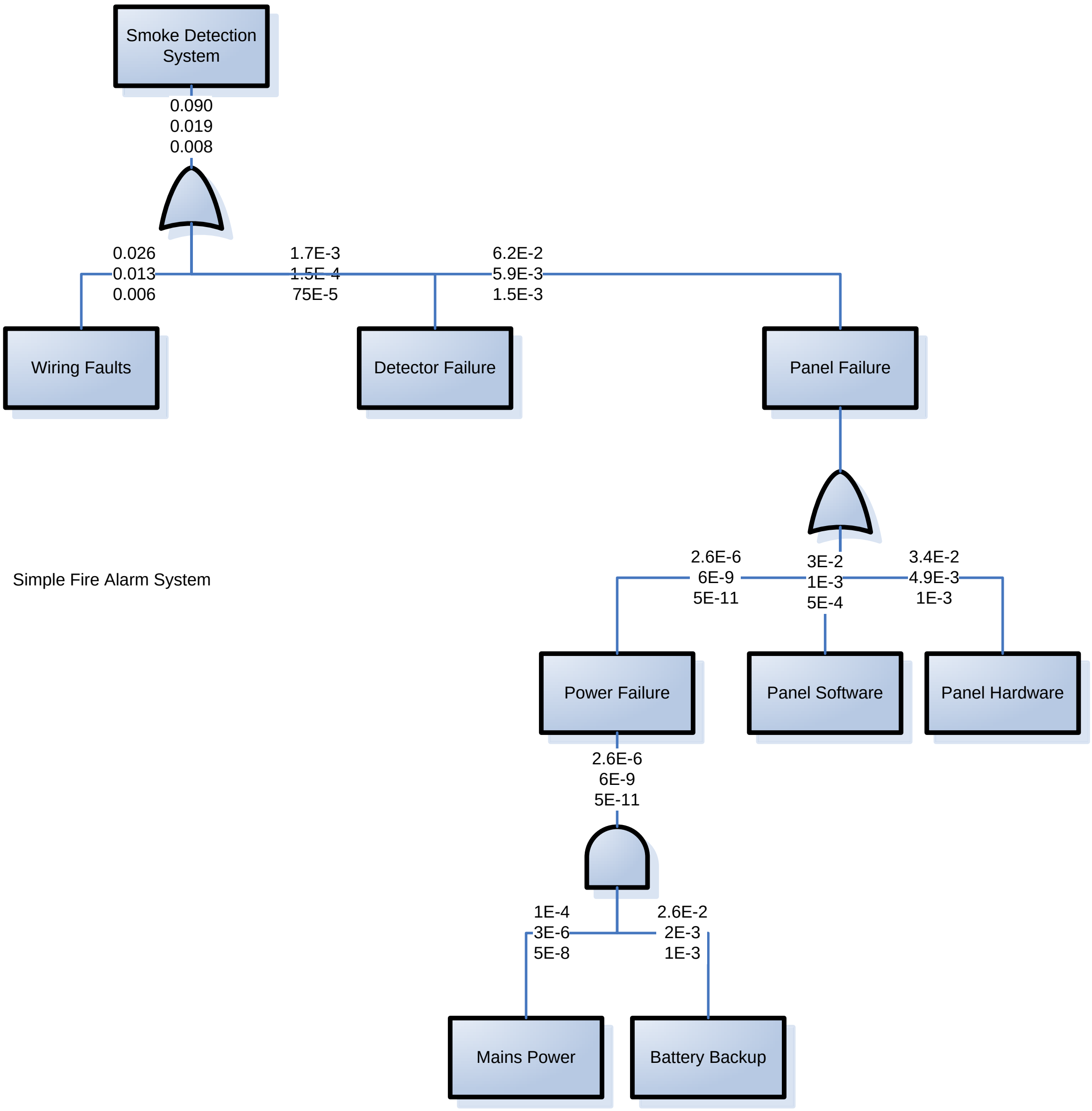


Figure B.7: Smoke Detection System Reliability Fault Tree

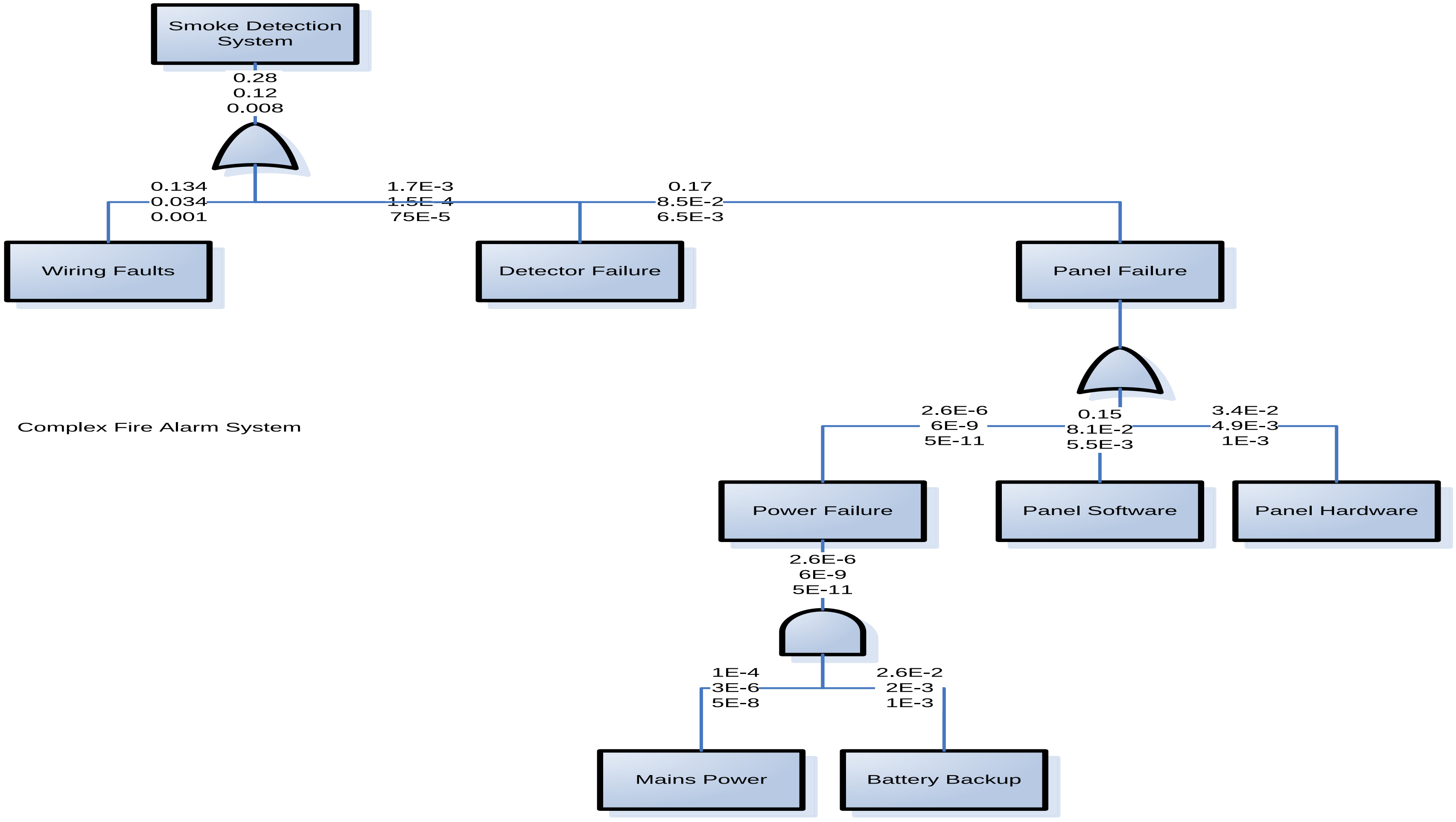


Figure B.8: Smoke Detection System Reliability Fault Tree

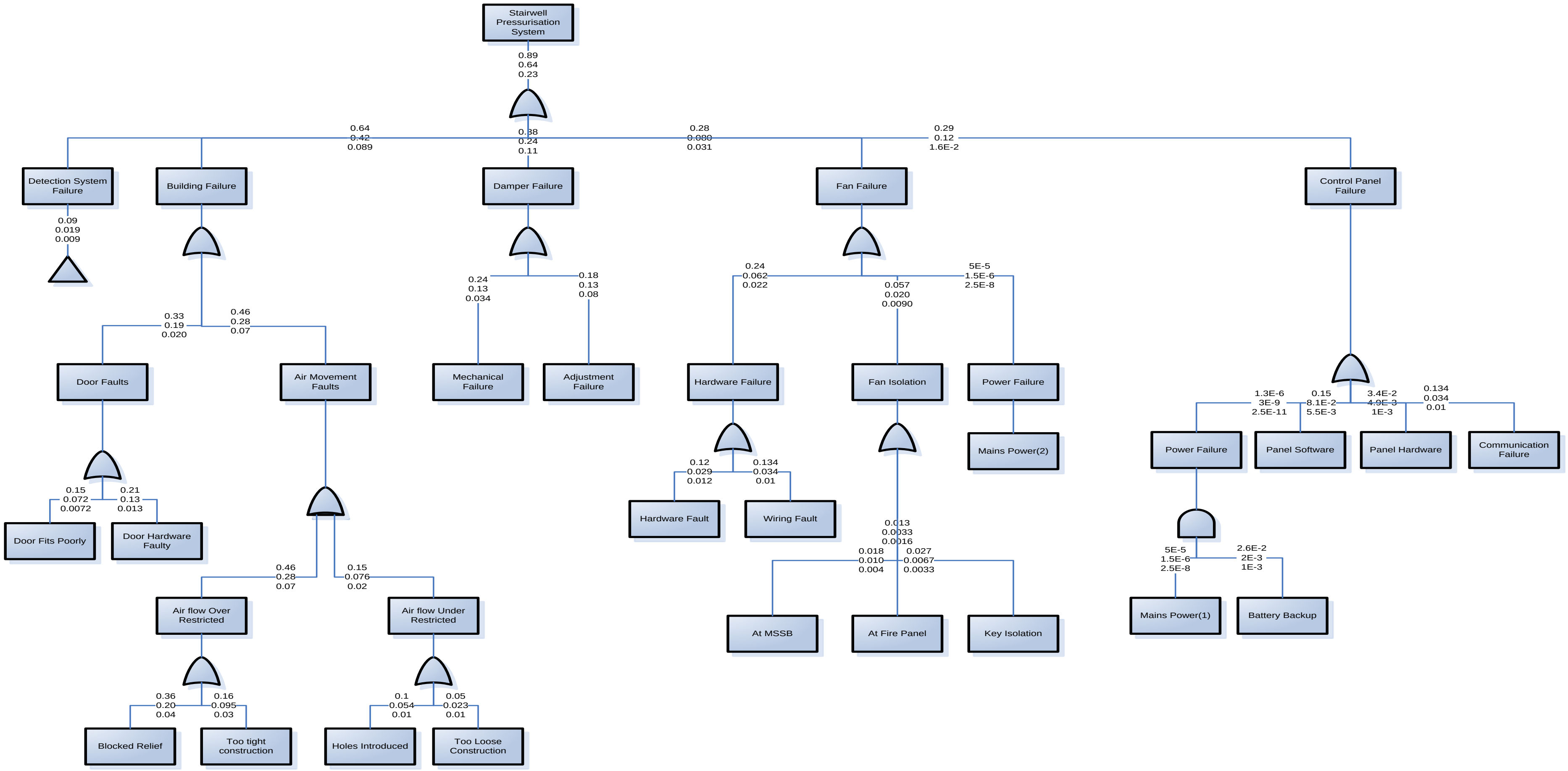


Figure B.9: Stairwell Pressurisation System Reliability Fault Tree

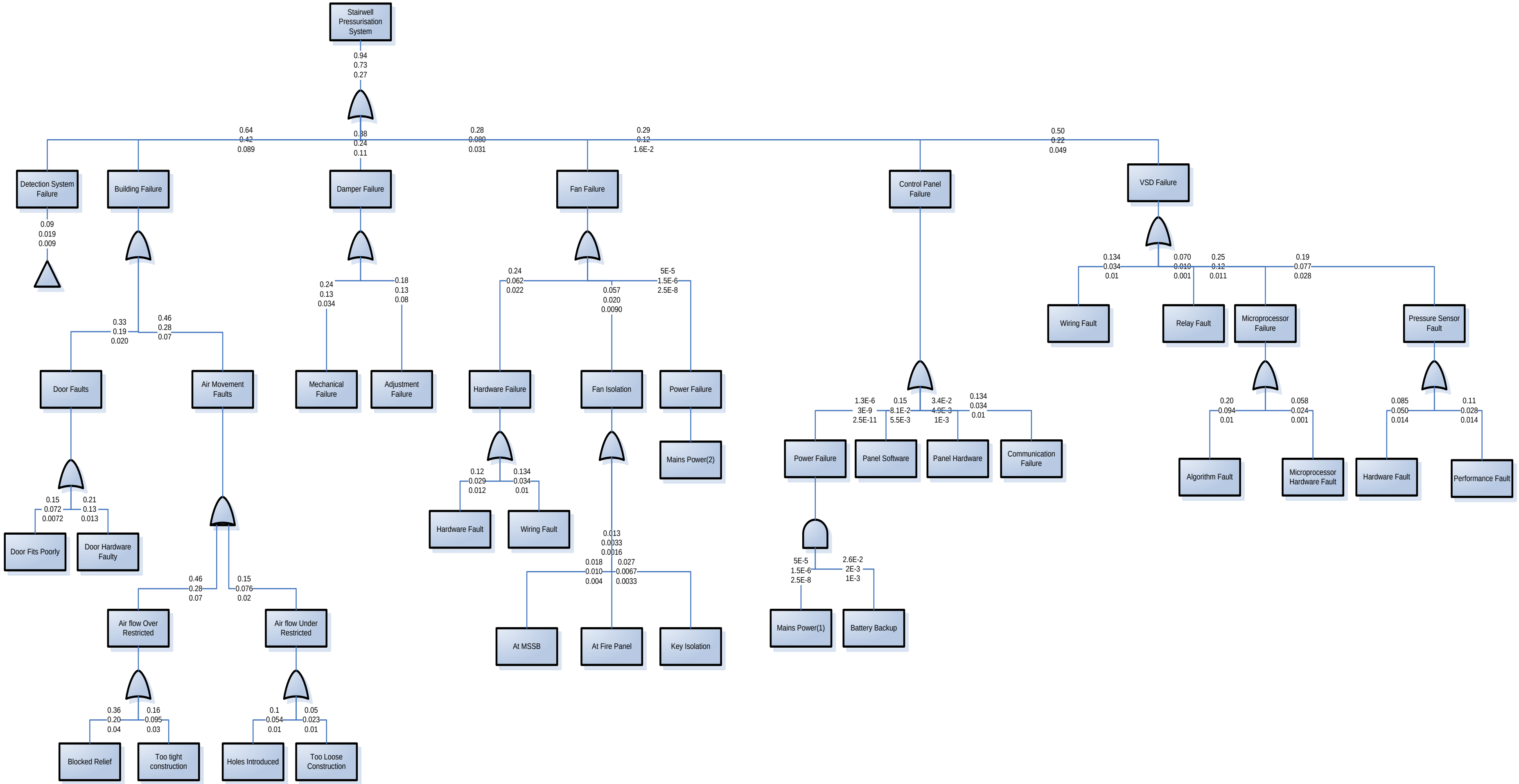


Figure B.10: Stairwell Pressurisation System Reliability Fault Tree

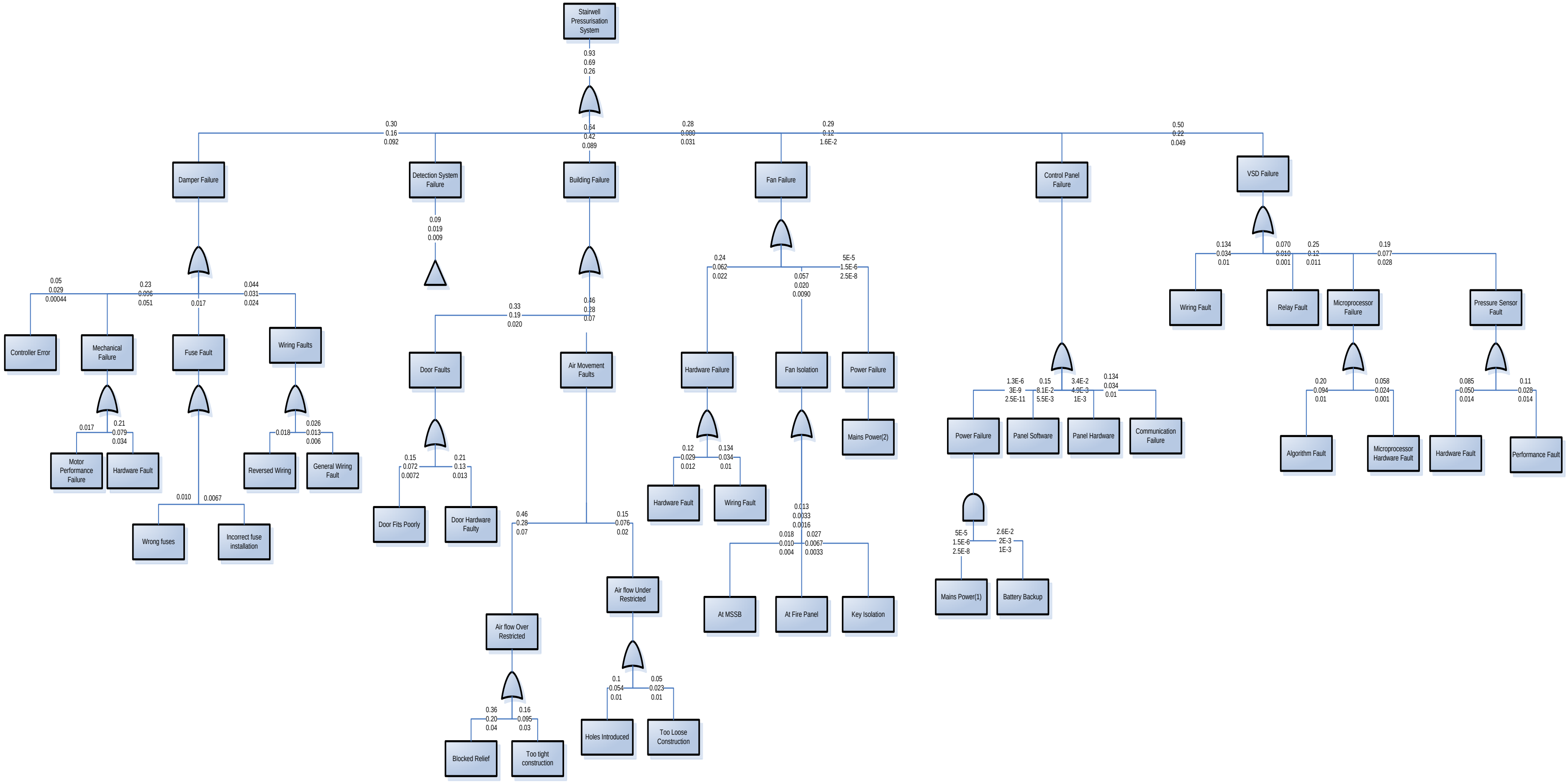
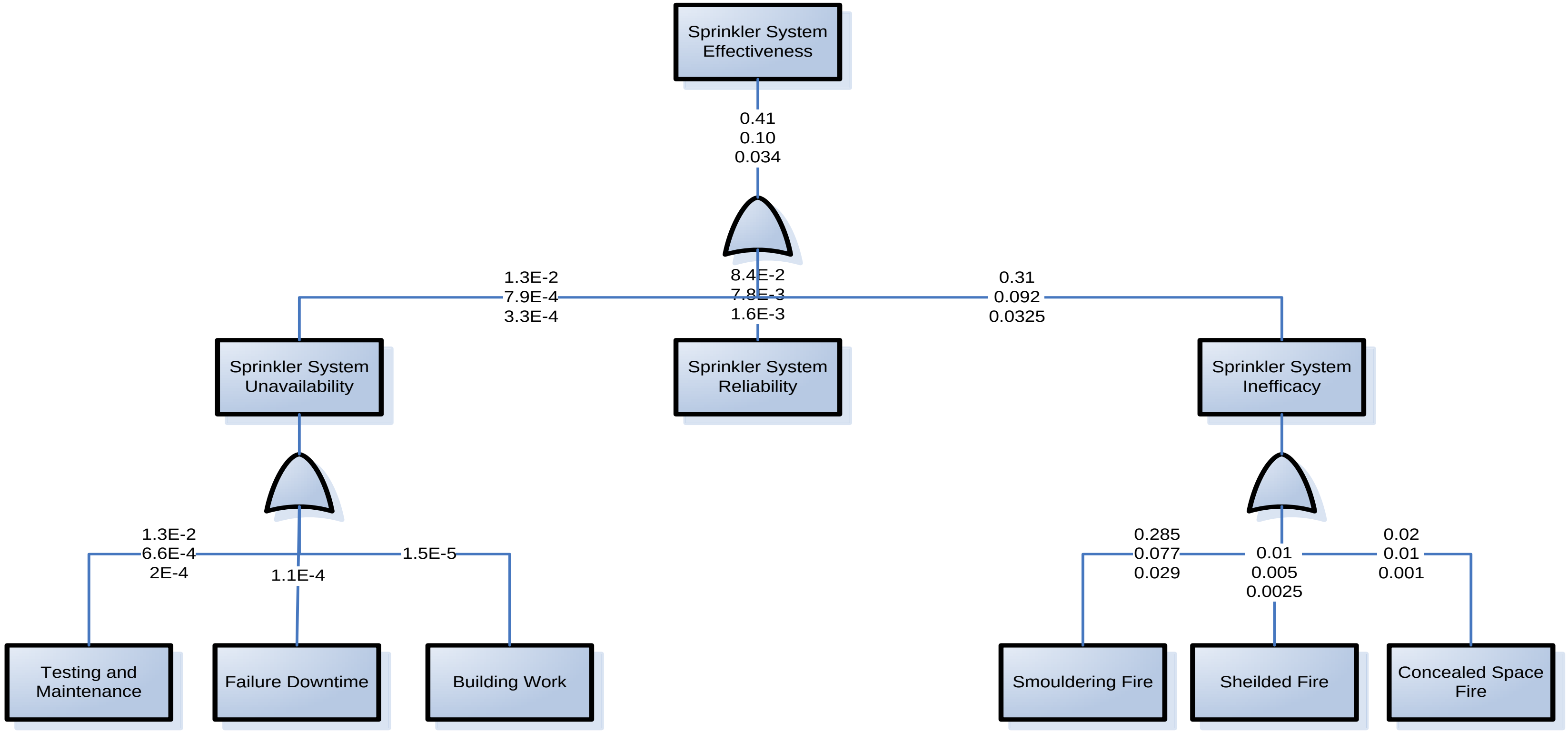


Figure B.11: Stairwell Pressurisation System Reliability Fault Tree

Appendix C

Effectiveness Fault Trees



Towns main single supply
Auckland
Analogue Addressable Panel
Apartment

Figure C.1: Sprinkler System Effectiveness Fault Tree

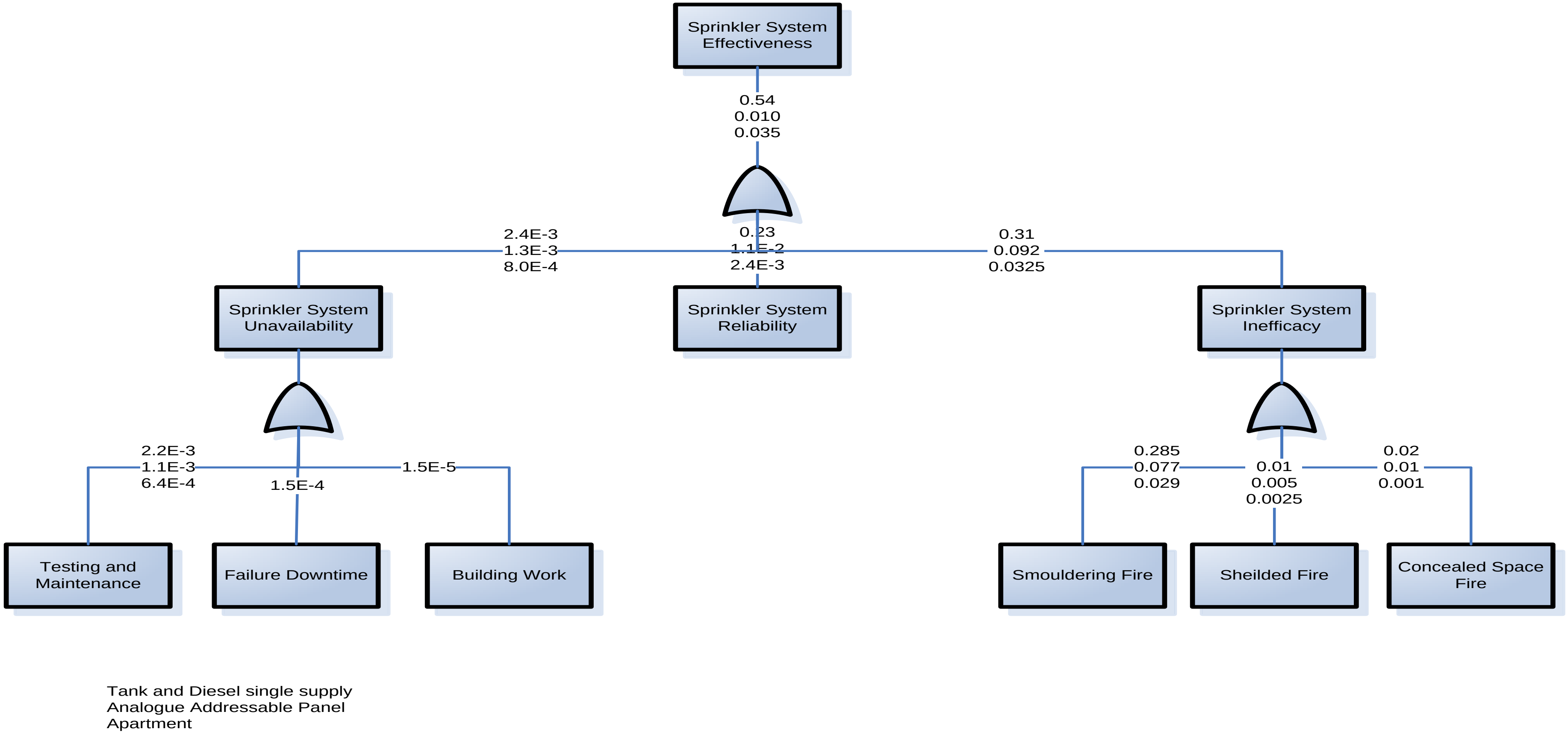
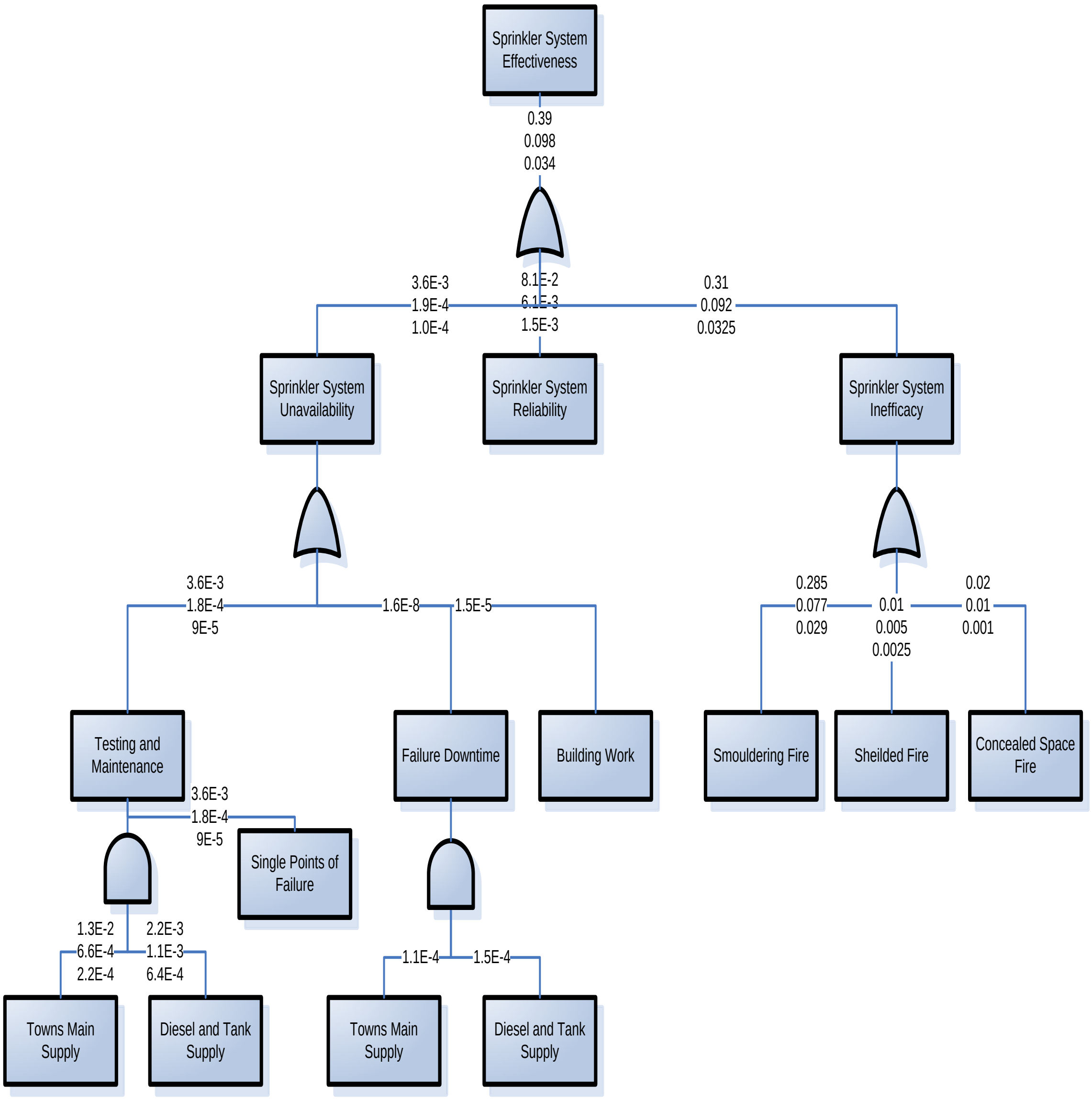
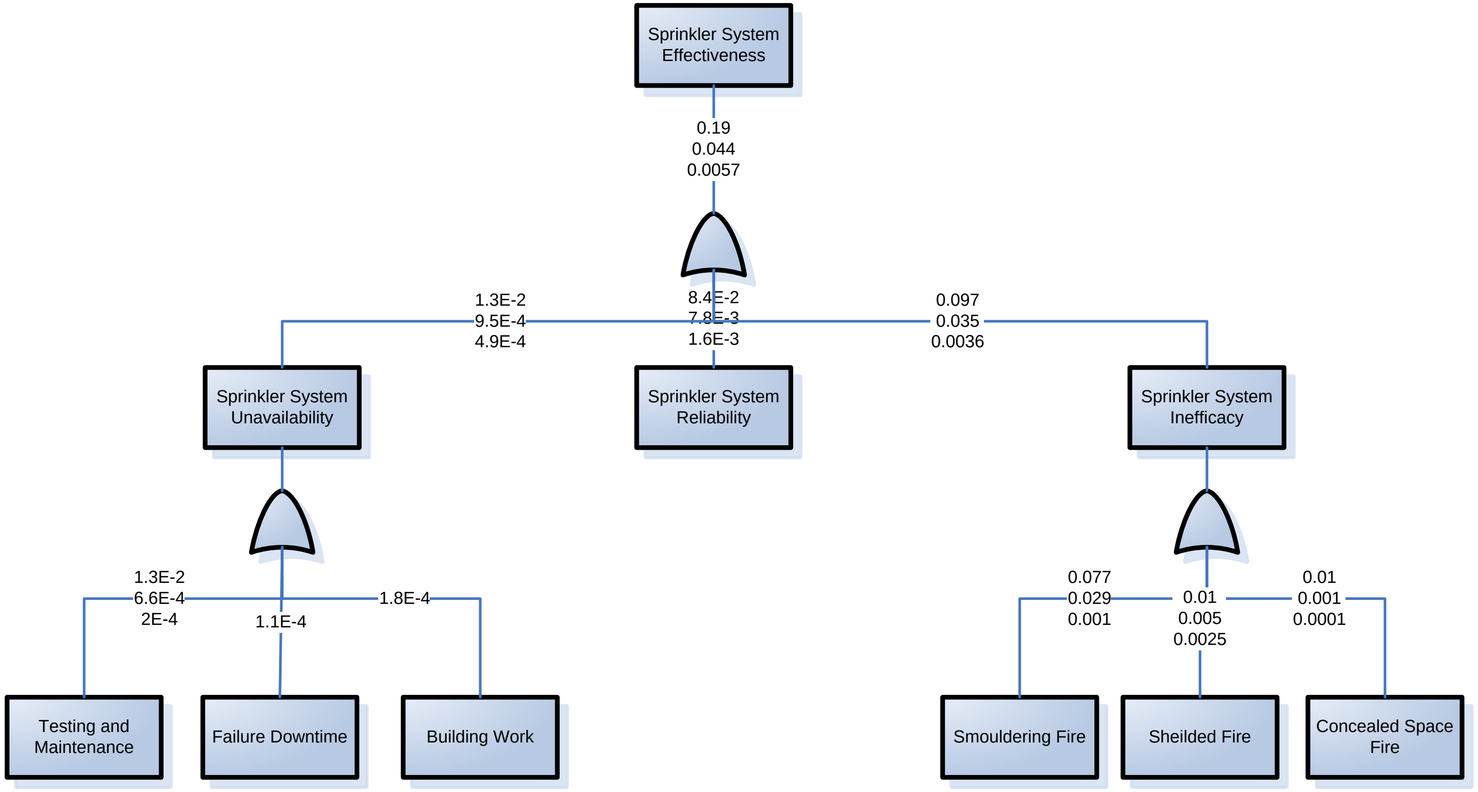


Figure C.2: Sprinkler System Effectiveness Fault Tree



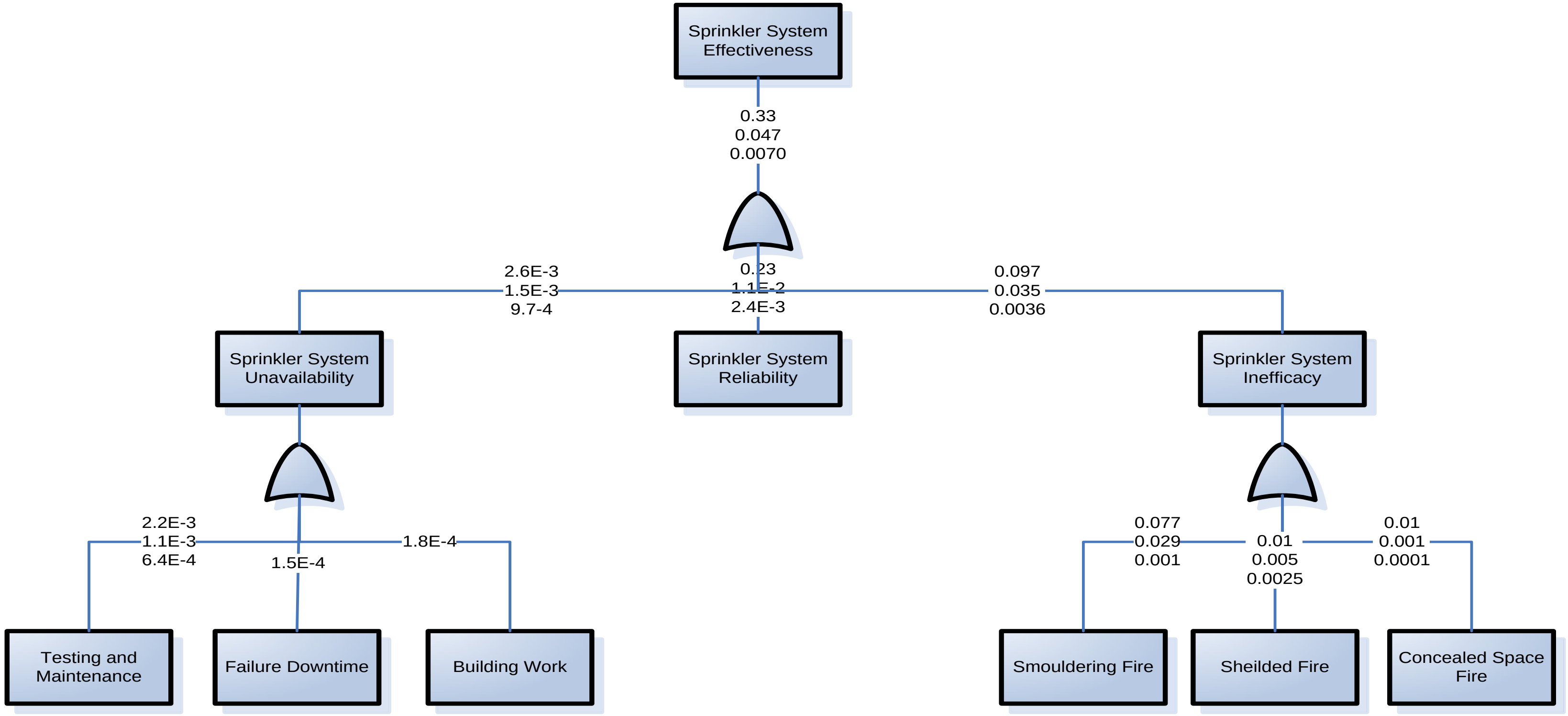
Tank and Diesel, Towns Main dual supply
Auckland
Analogue Addressable Panel
Apartment

Figure C.3: Sprinkler System Effectiveness Fault Tree



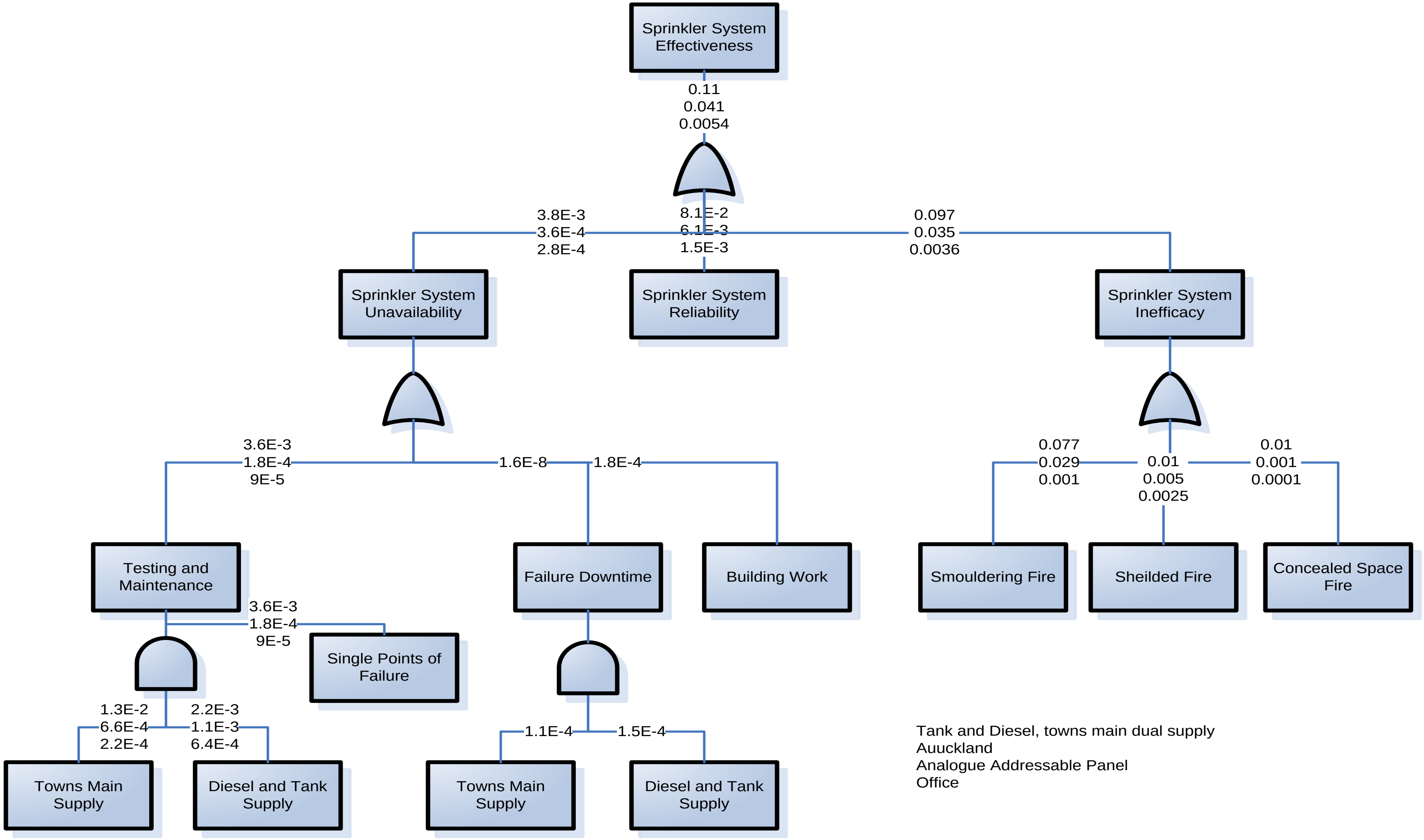
Towns main single supply
Auckland
Analogue Addressable Panel
Office

Figure C.4: Sprinkler System Effectiveness Fault Tree



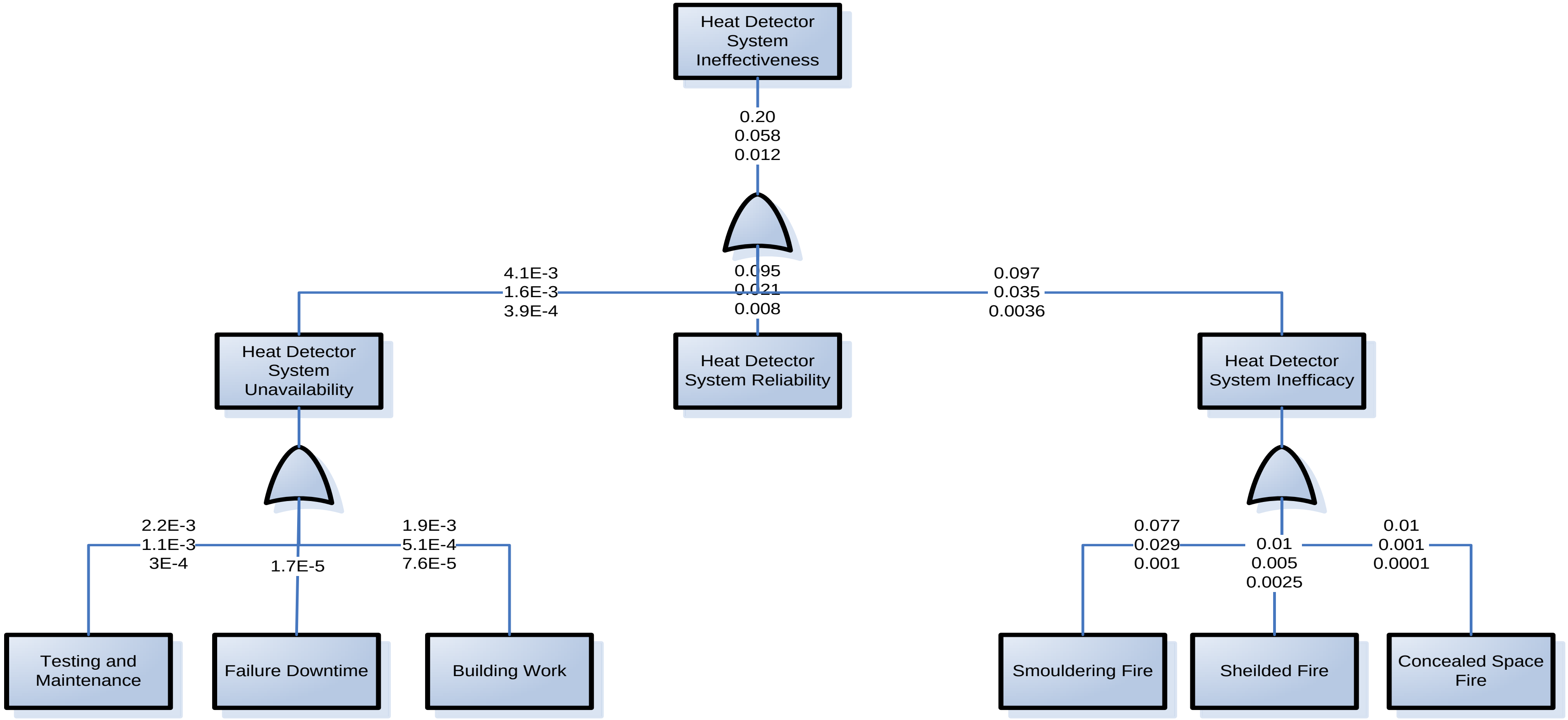
Tank and Diesel single supply
Analogue Addressable Panel
Office

Figure C.5: Sprinkler System Effectiveness Fault Tree



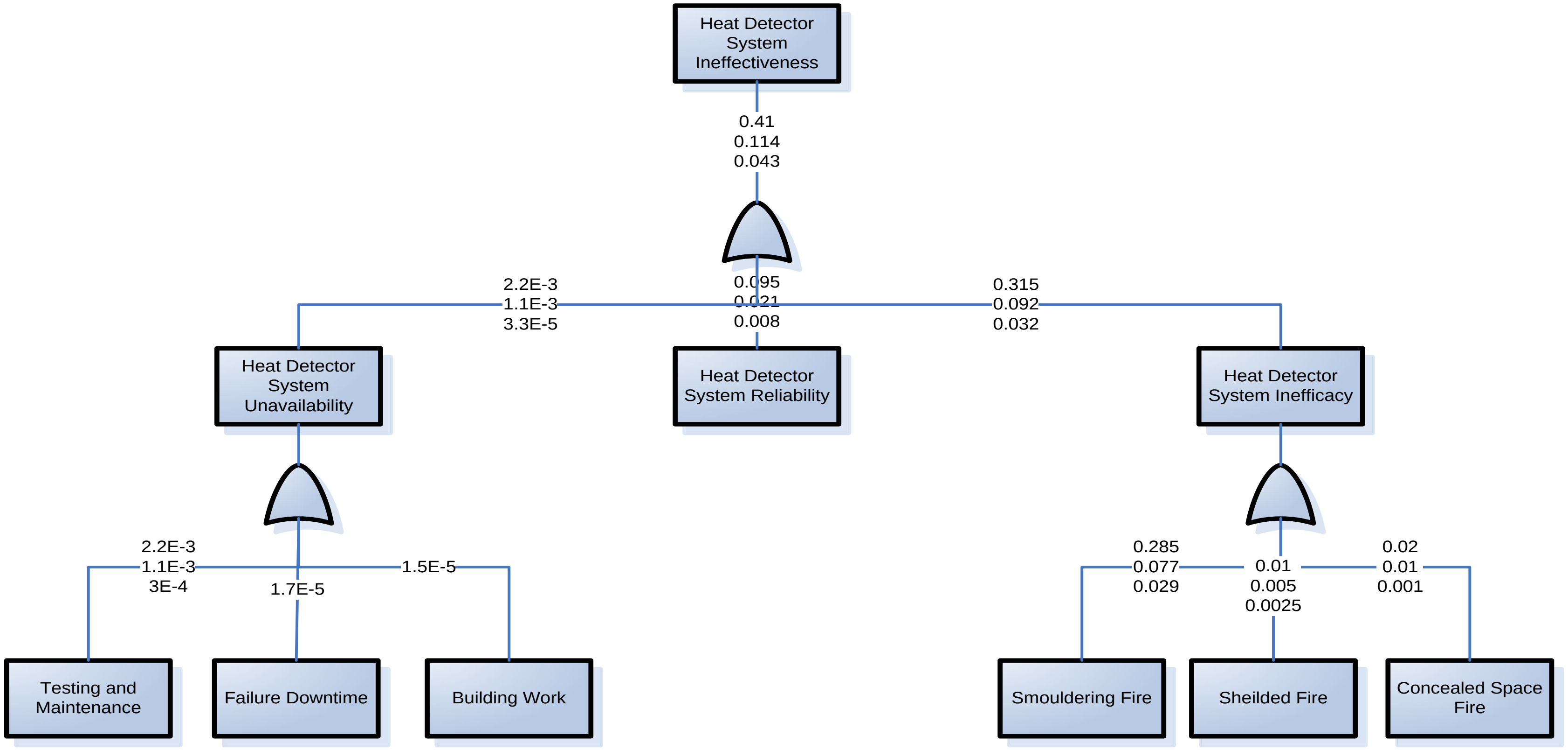
Tank and Diesel, towns main dual supply
Auuckland
Analogue Addressable Panel
Office

Figure C.6: Sprinkler System Effectiveness Fault Tree



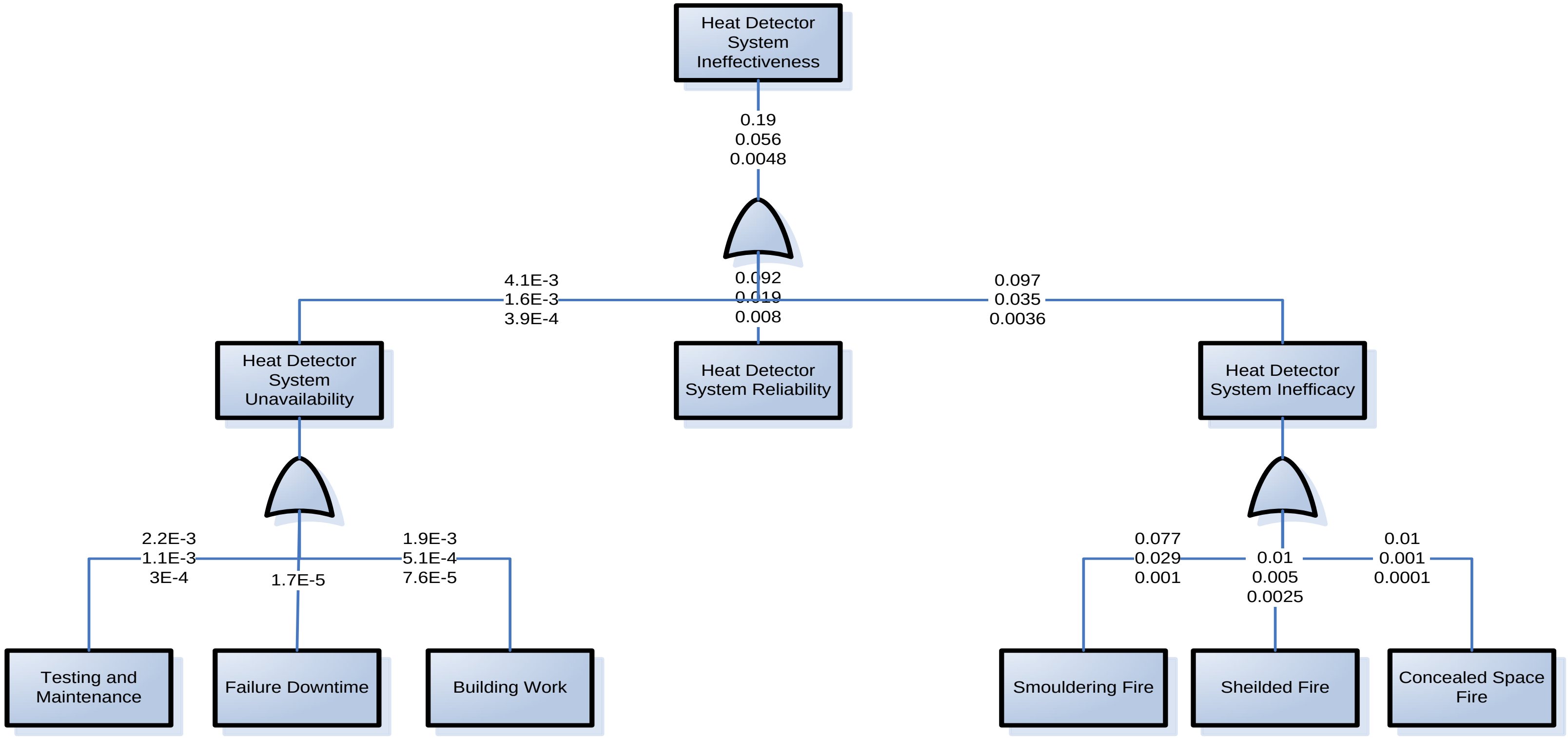
Heat Detection System (simple)
Less reliable detectors
Analogue Addressable Panel
Office

Figure C.7: Heat Detector System Effectiveness Fault Tree



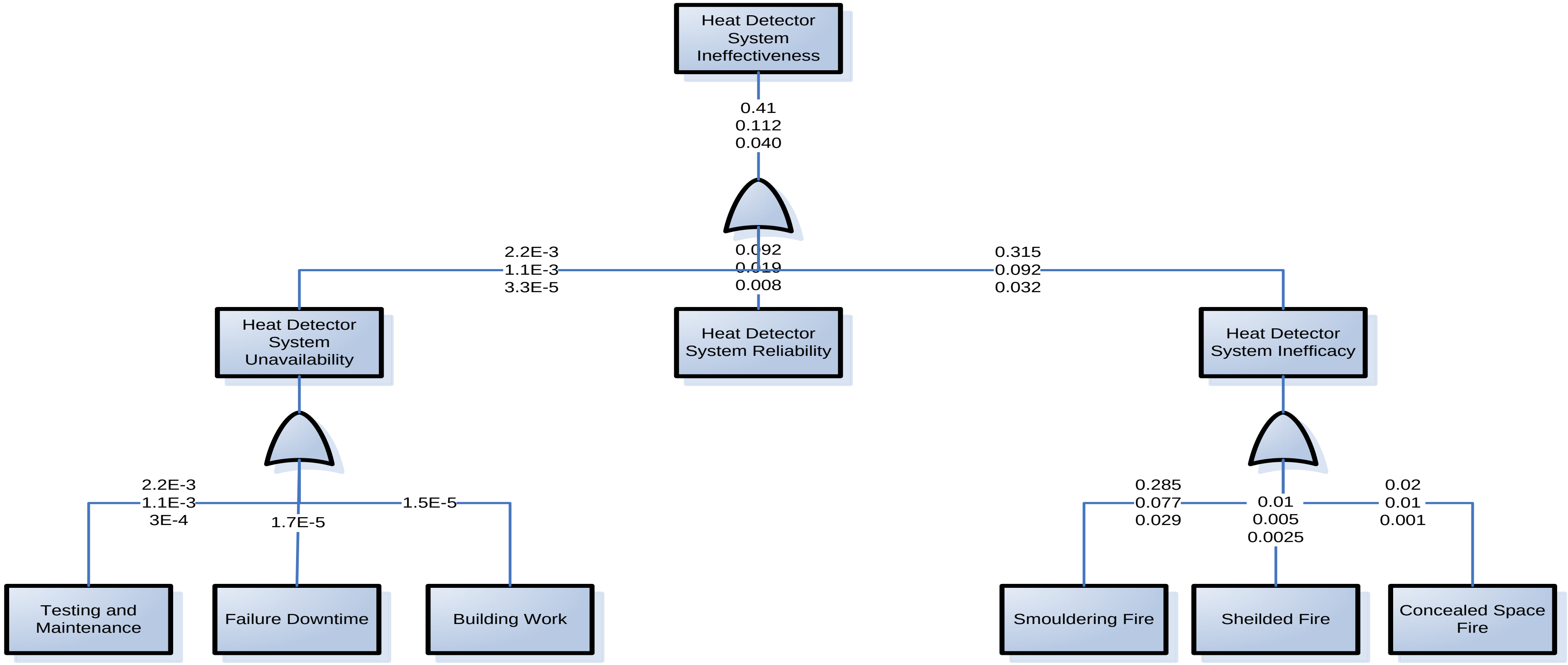
Heat Detection System (simple)
Analogue Addressable Panel
Less reliable detectors
Apartment

Figure C.8: Heat Detector System Effectiveness Fault Tree



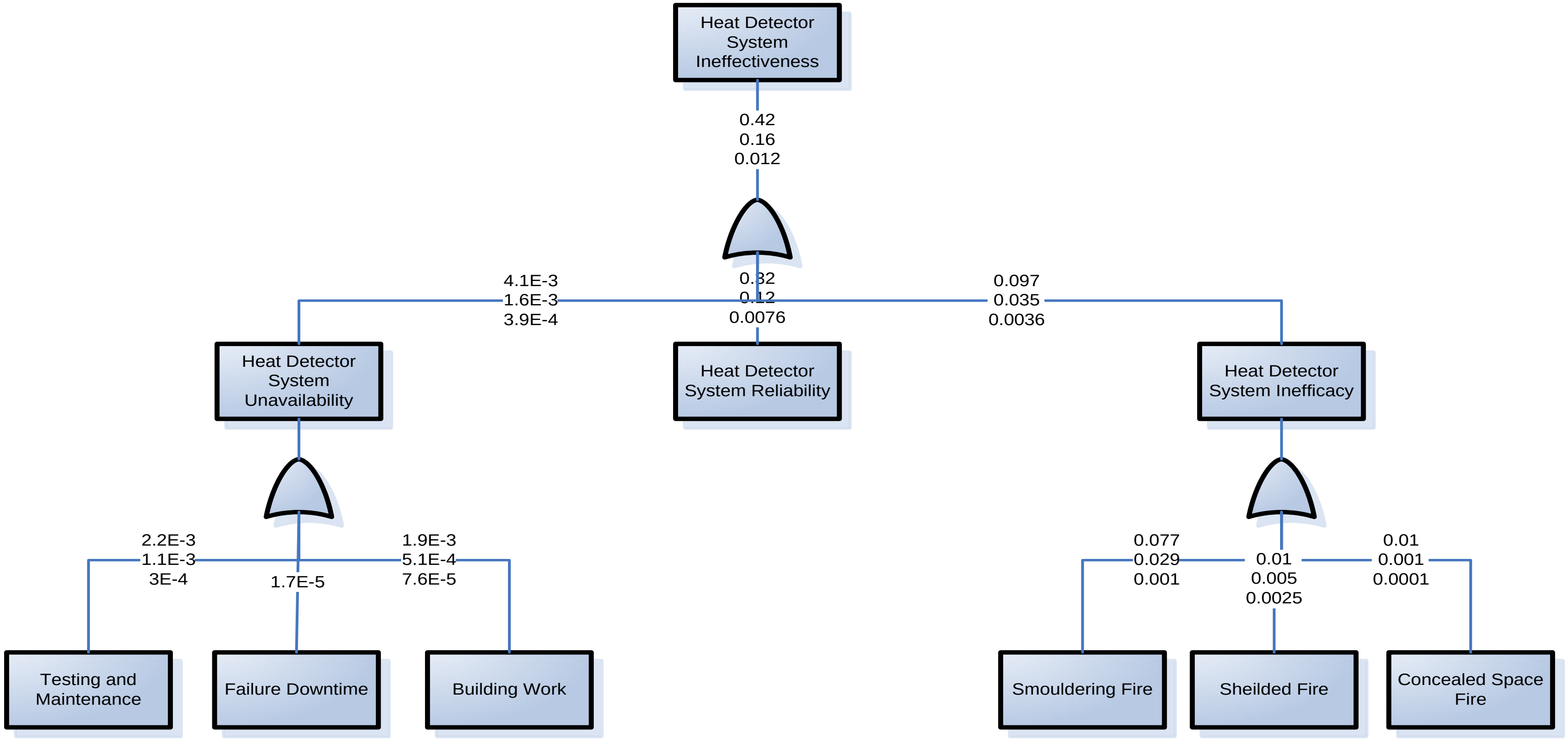
Heat Detection System (simple)
More reliable detectors
Analogue Addressable Panel
Office

Figure C.9: Heat Detector System Effectiveness Fault Tree



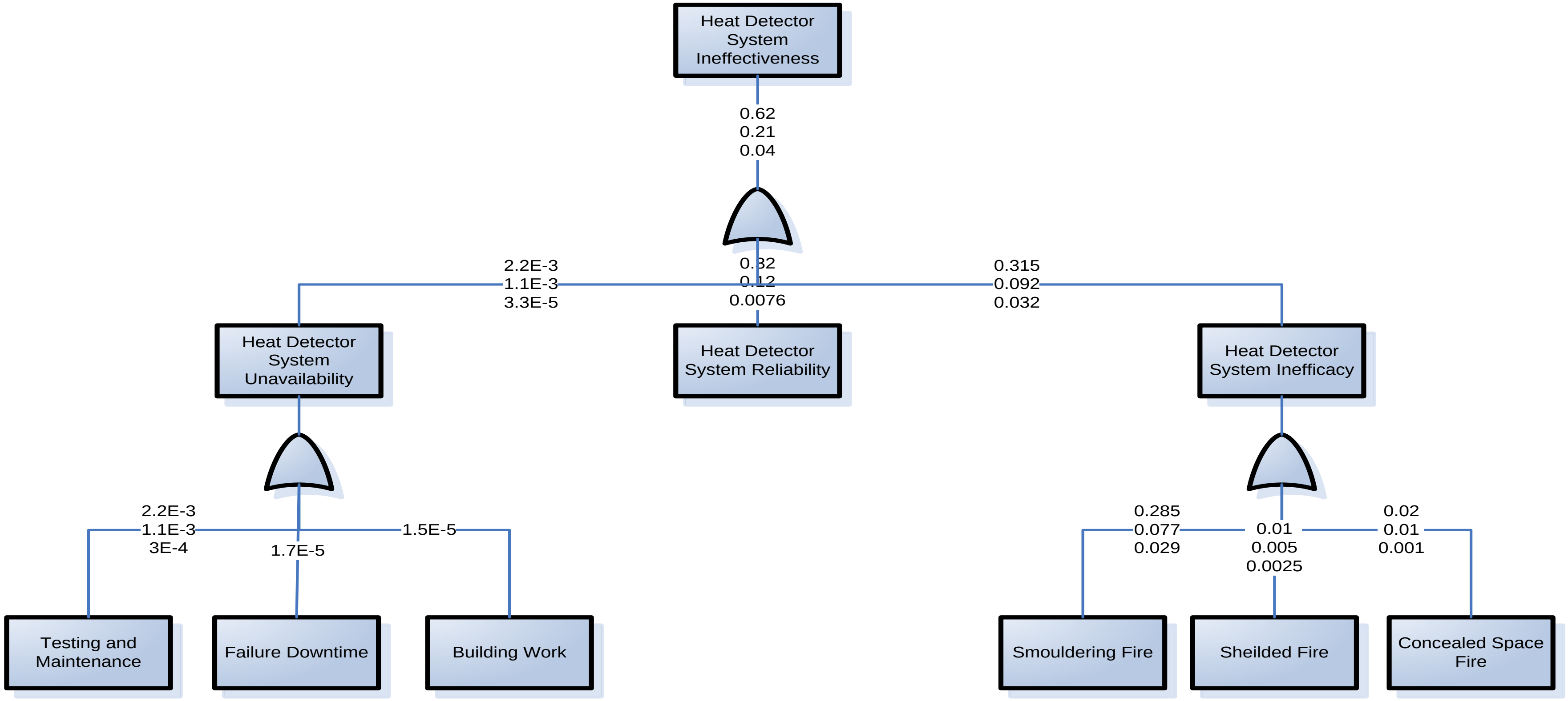
Heat Detection System (simple)
More reliable detectors
Analogue Addressable Panel
Apartment

Figure C.10: Heat Detector System Effectiveness Fault Tree



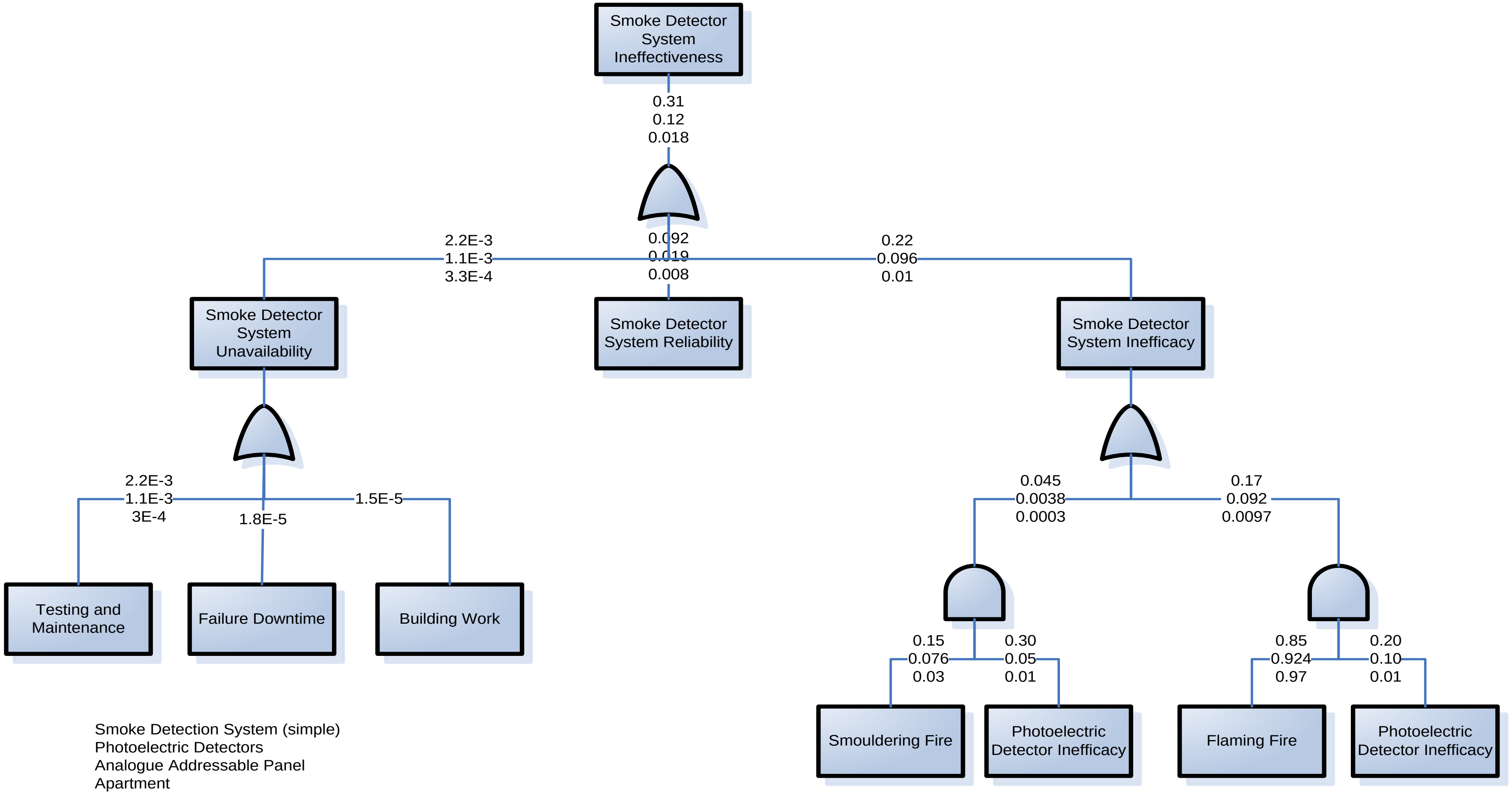
Heat Detection System (complex)
Analogue Addressable Panel
Office

Figure C.11: Heat Detector System Effectiveness Fault Tree



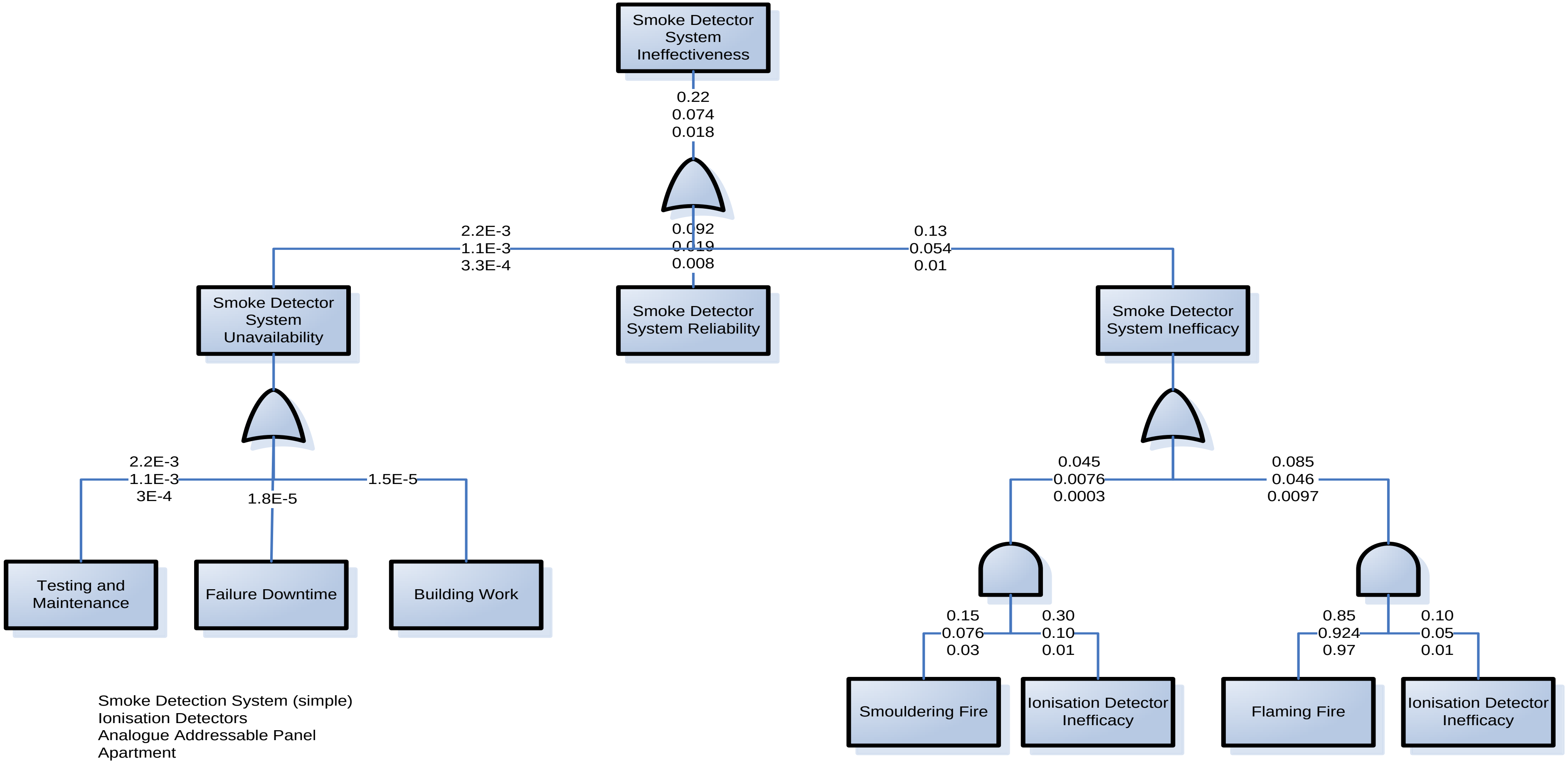
Heat Detection System (complex)
Analogue Addressable Panel
Apartment

Figure C.12: Heat Detector System Effectiveness Fault Tree



Smoke Detection System (simple)
Photoelectric Detectors
Analogue Addressable Panel
Apartment
Detectors in fire room

Figure C.13: Smoke Detector System Effectiveness Fault Tree



Smoke Detection System (simple)
Ionisation Detectors
Analogue Addressable Panel
Apartment
Detectors in fire room

Figure C.14: Smoke Detector System Effectiveness Fault Tree

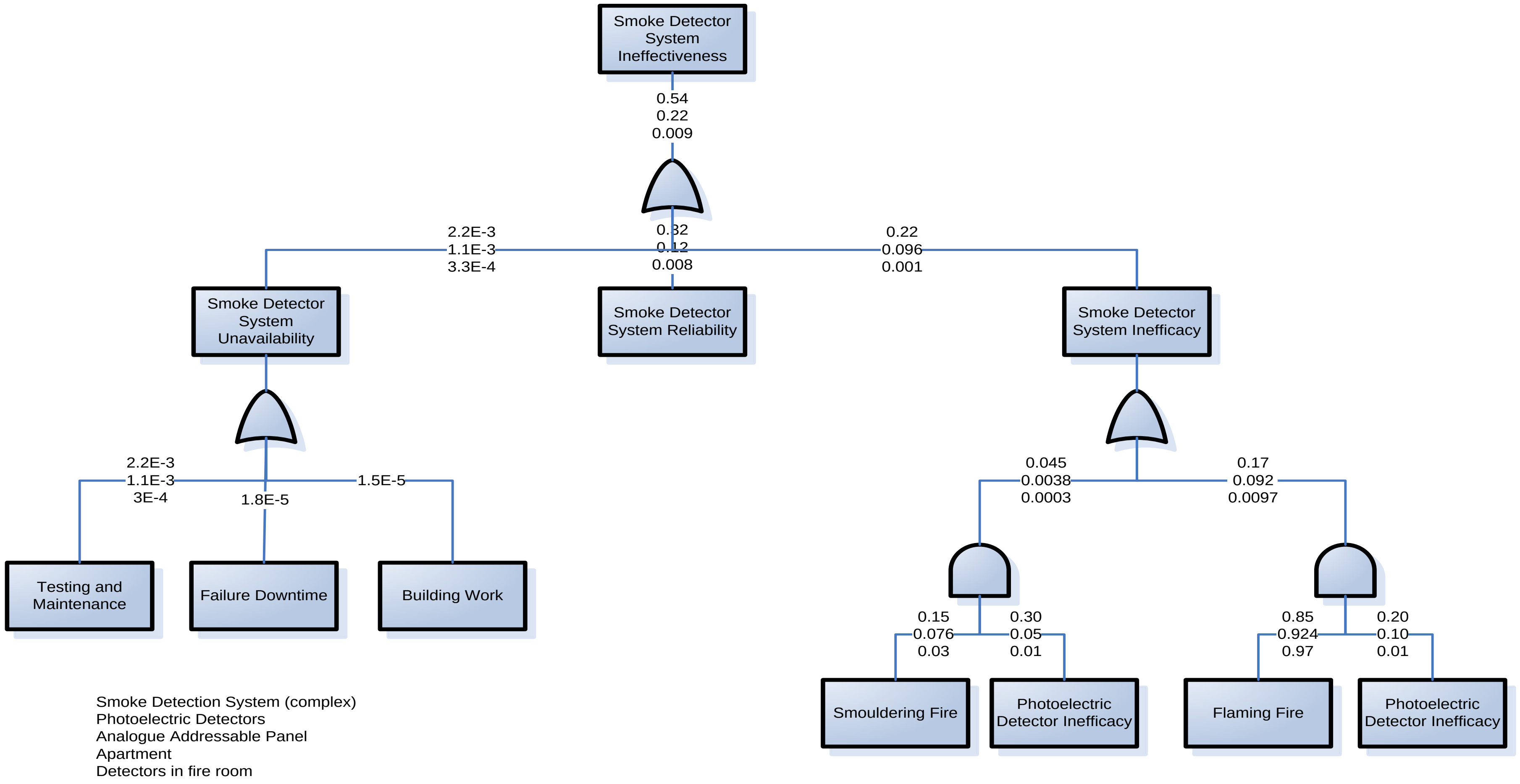
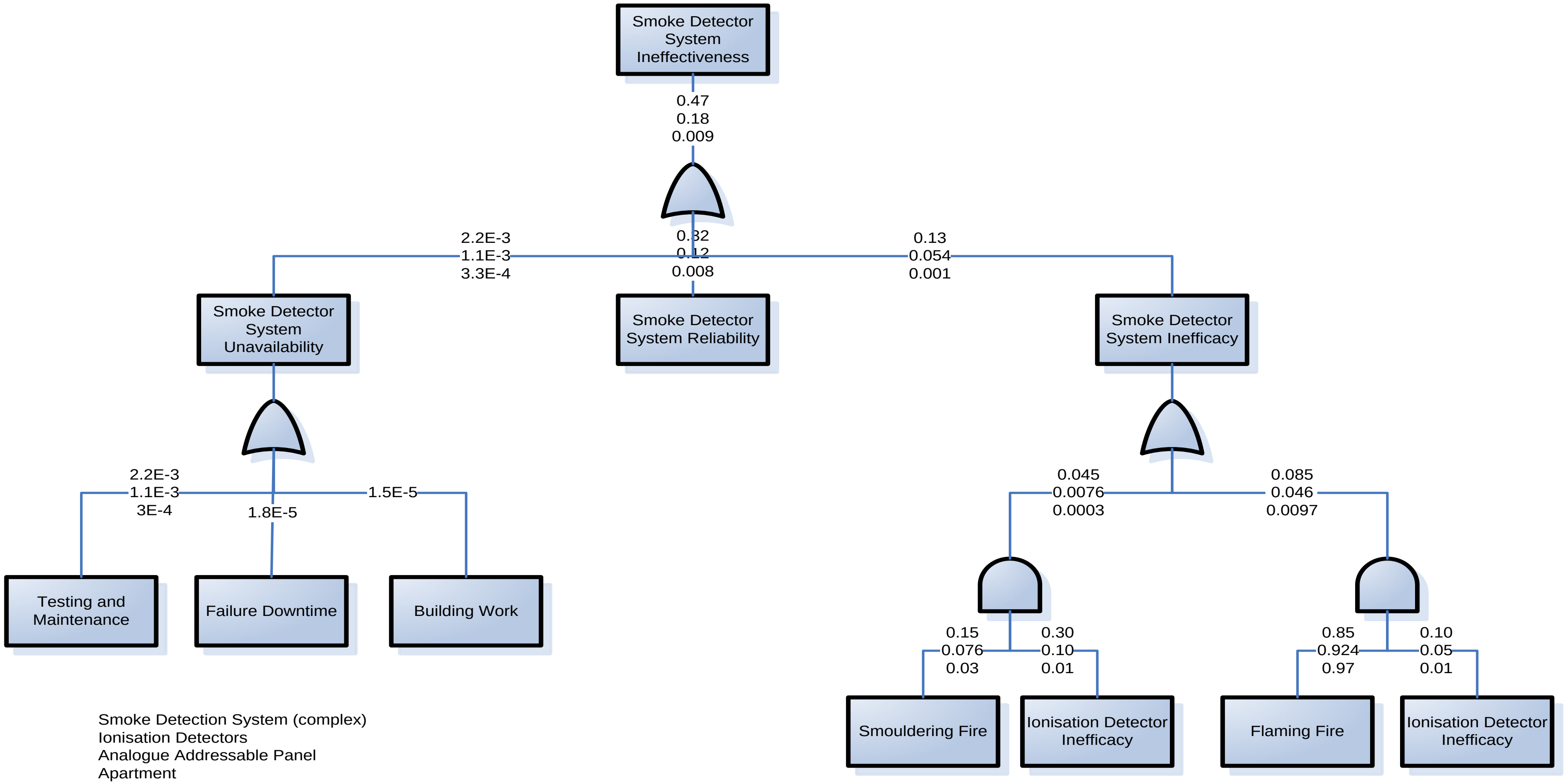
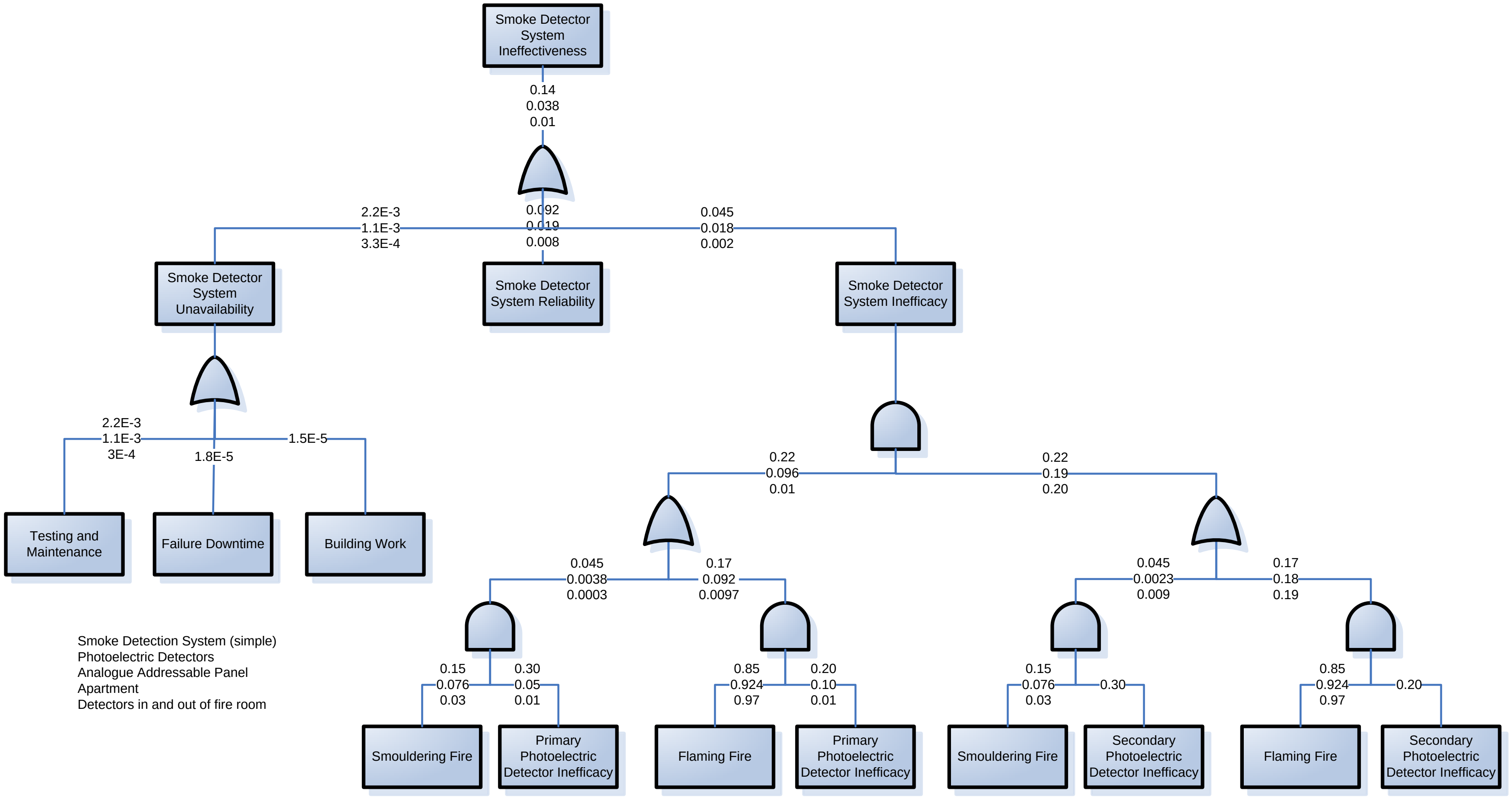


Figure C.14: Smoke Detector System Effectiveness Fault Tree



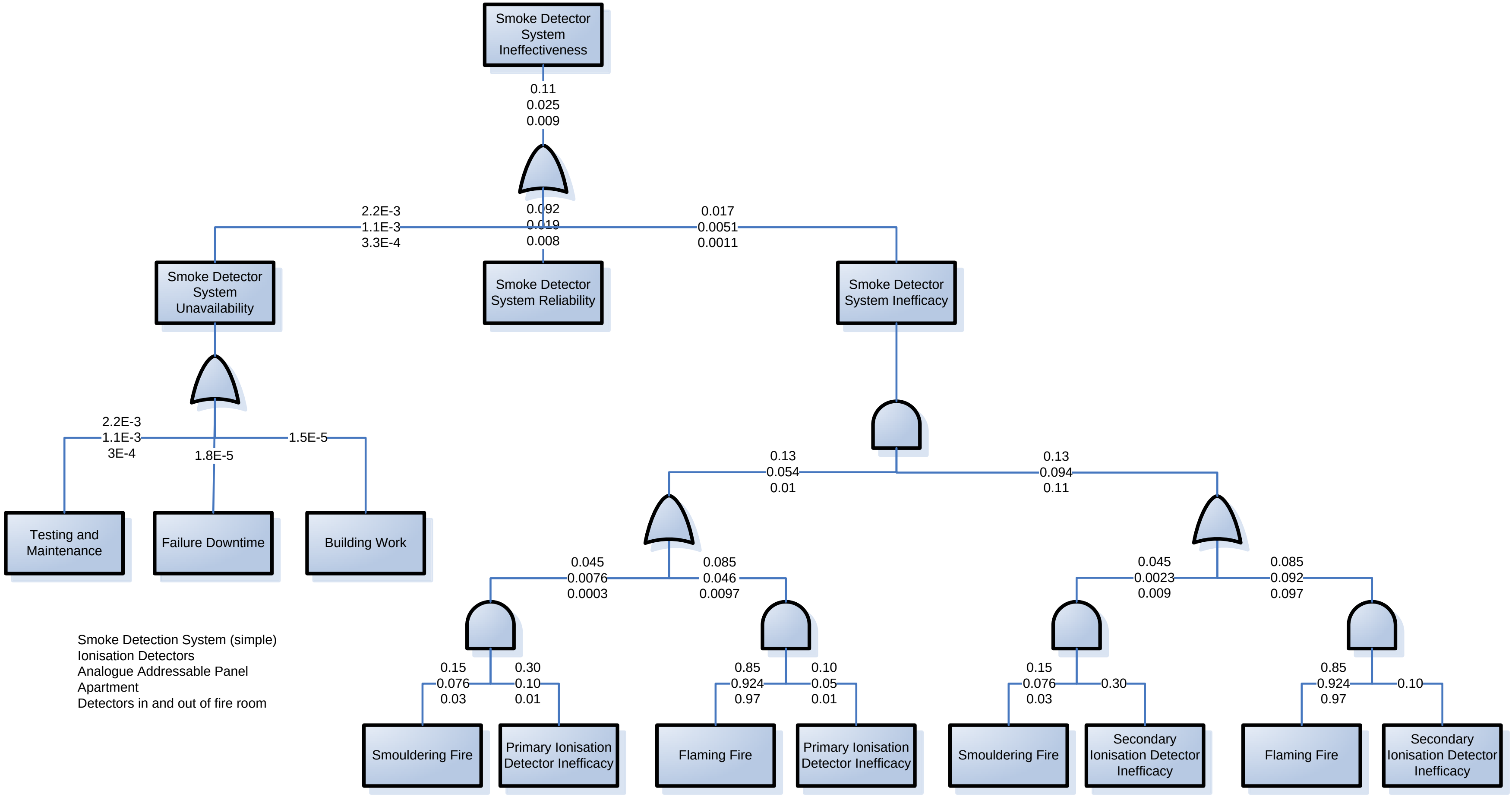
Smoke Detection System (complex)
Ionisation Detectors
Analogue Addressable Panel
Apartment
Detectors in fire room

Figure C.15: Smoke Detector System Effectiveness Fault Tree



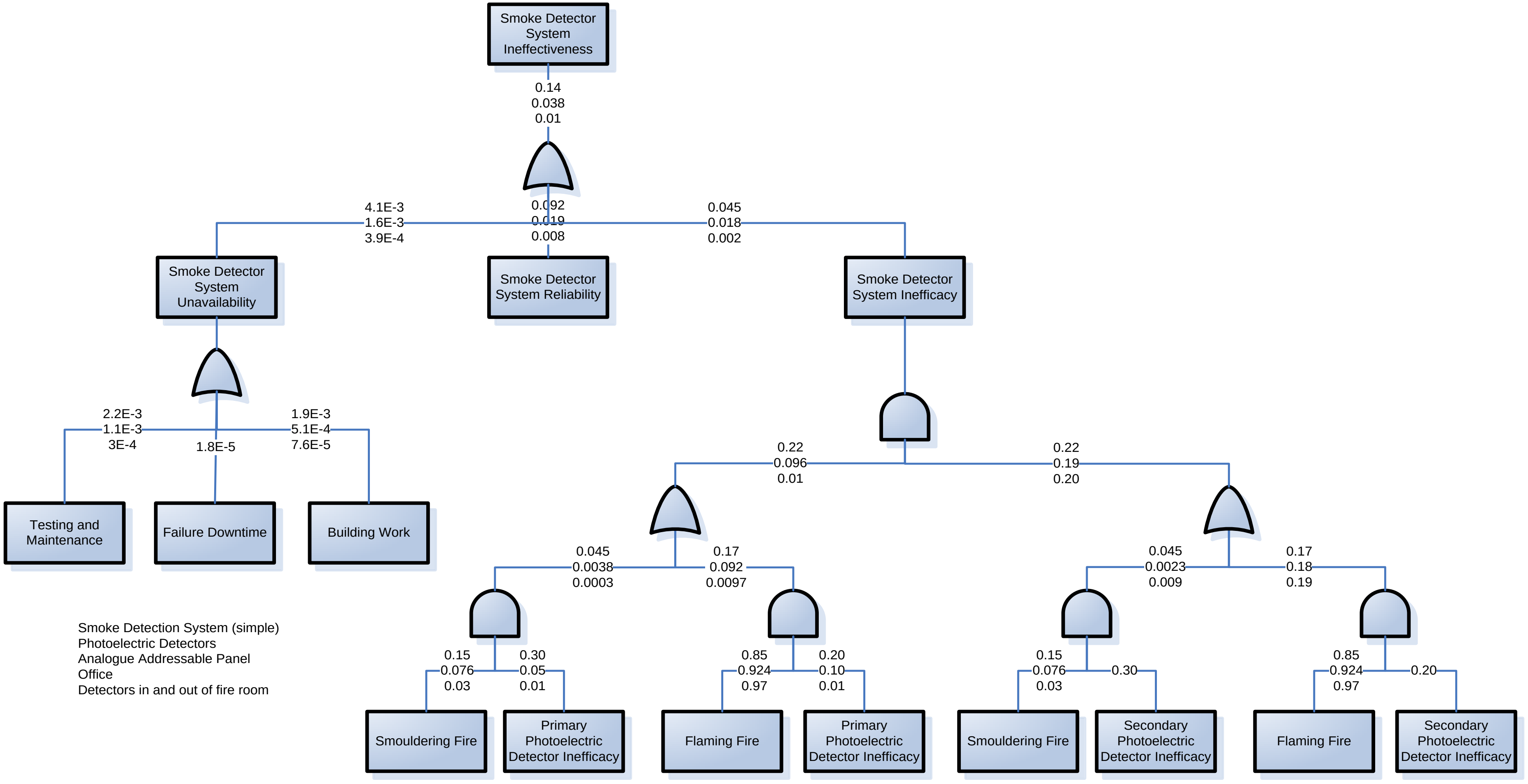
Smoke Detection System (simple)
Photoelectric Detectors
Analogue Addressable Panel
Apartment
Detectors in and out of fire room

Figure C.16: Smoke Detector System Effectiveness Fault Tree



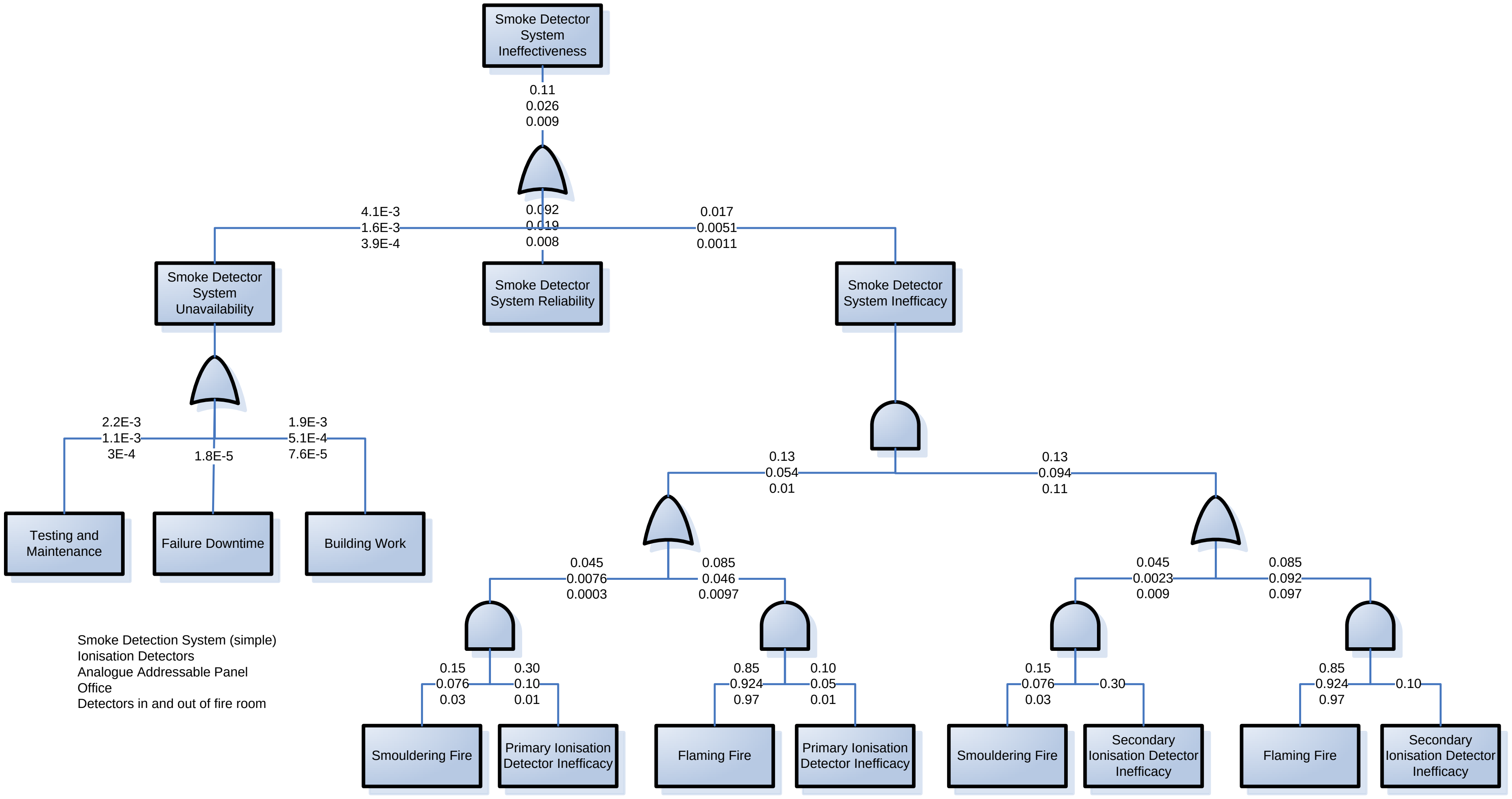
Smoke Detection System (simple)
Ionisation Detectors
Analogue Addressable Panel
Apartment
Detectors in and out of fire room

Figure C.17: Smoke Detector System Effectiveness Fault Tree



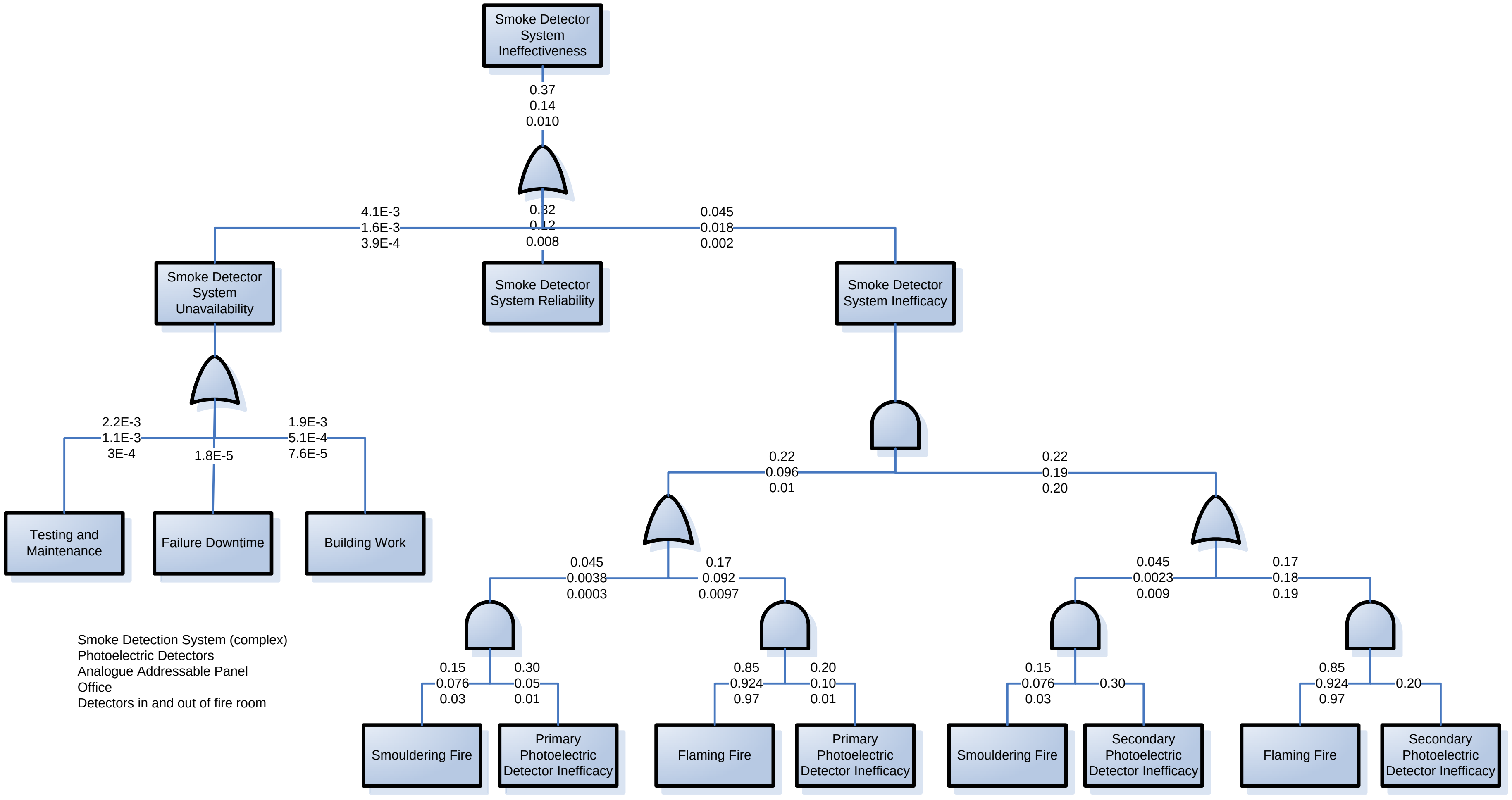
Smoke Detection System (simple)
Photoelectric Detectors
Analogue Addressable Panel
Office
Detectors in and out of fire room

Figure C.18: Smoke Detector System Effectiveness Fault Tree



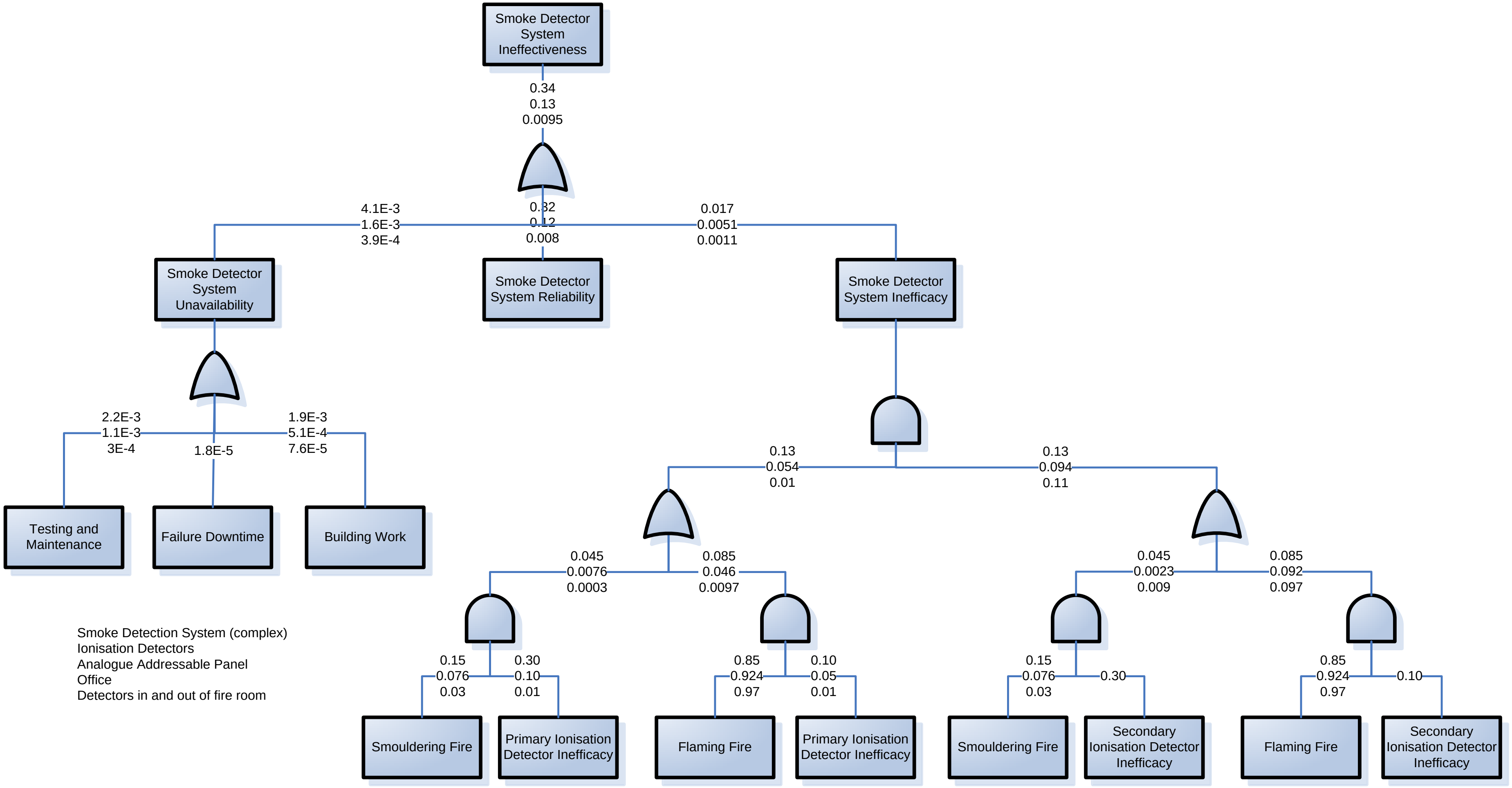
Smoke Detection System (simple)
Ionisation Detectors
Analogue Addressable Panel
Office
Detectors in and out of fire room

Figure C.19: Smoke Detector System Effectiveness Fault Tree



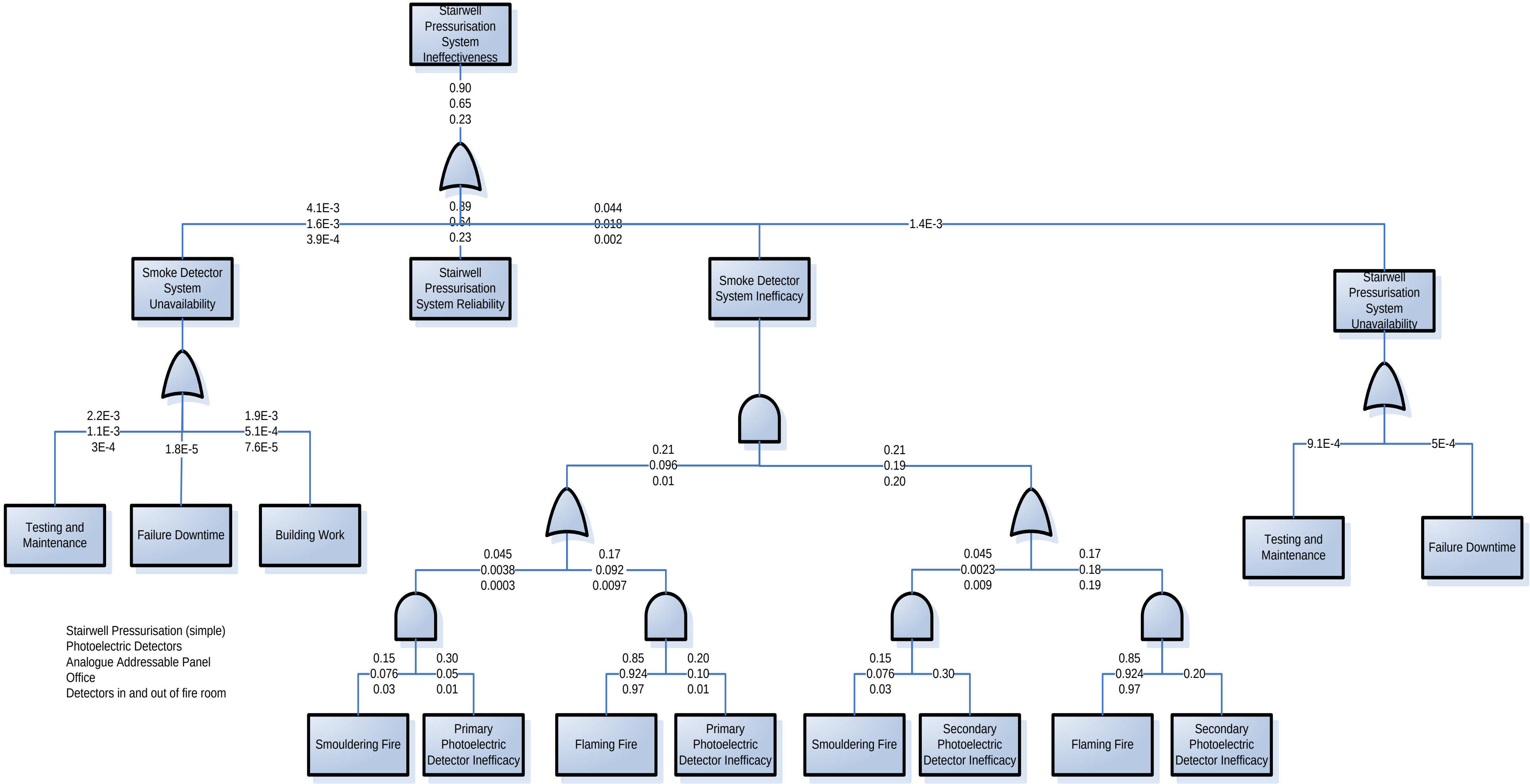
Smoke Detection System (complex)
Photoelectric Detectors
Analogue Addressable Panel
Office
Detectors in and out of fire room

Figure C.20: Smoke Detector System Effectiveness Fault Tree



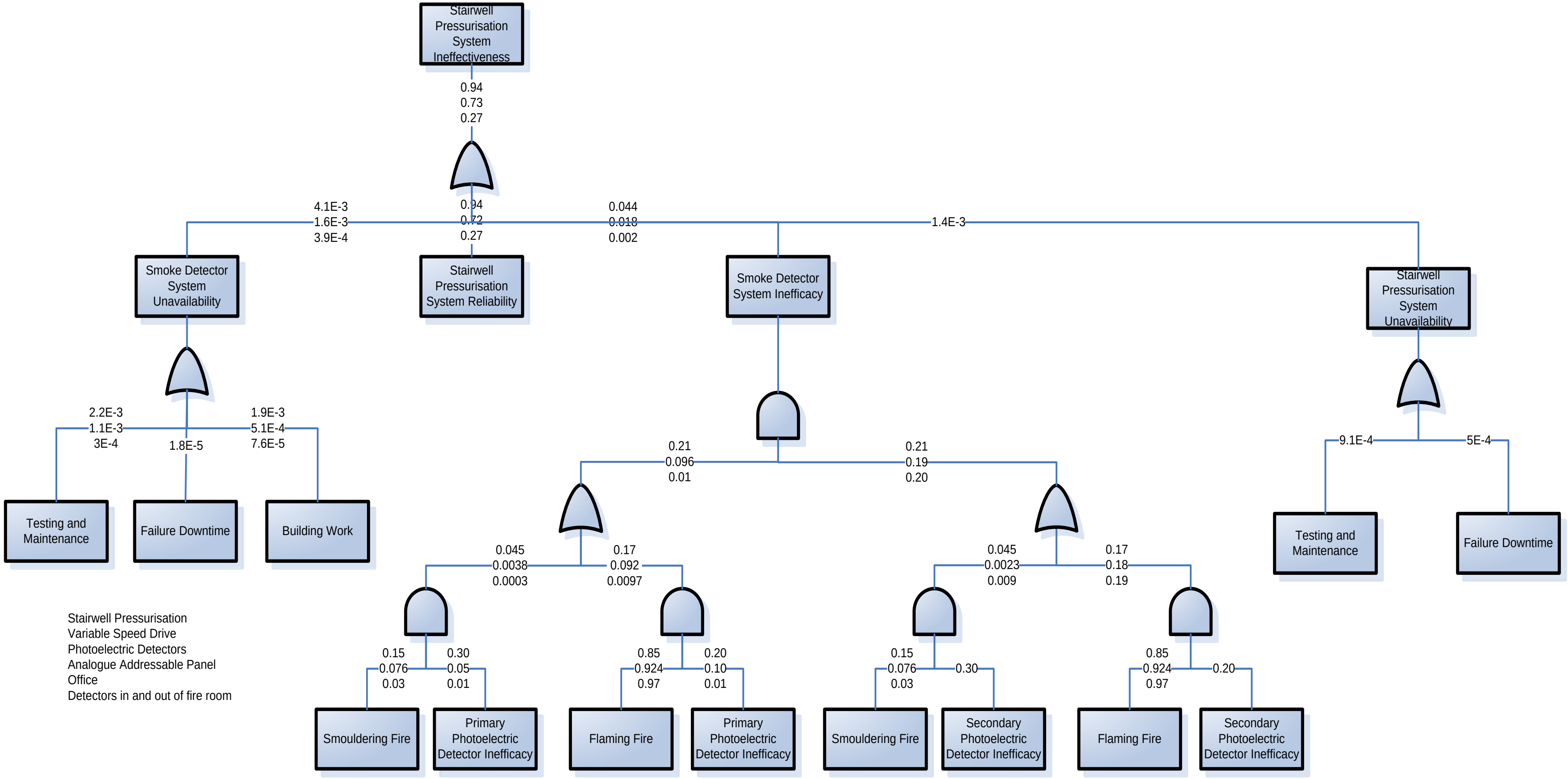
Smoke Detection System (complex)
Ionisation Detectors
Analogue Addressable Panel
Office
Detectors in and out of fire room

Figure C.21: Smoke Detector System Effectiveness Fault Tree



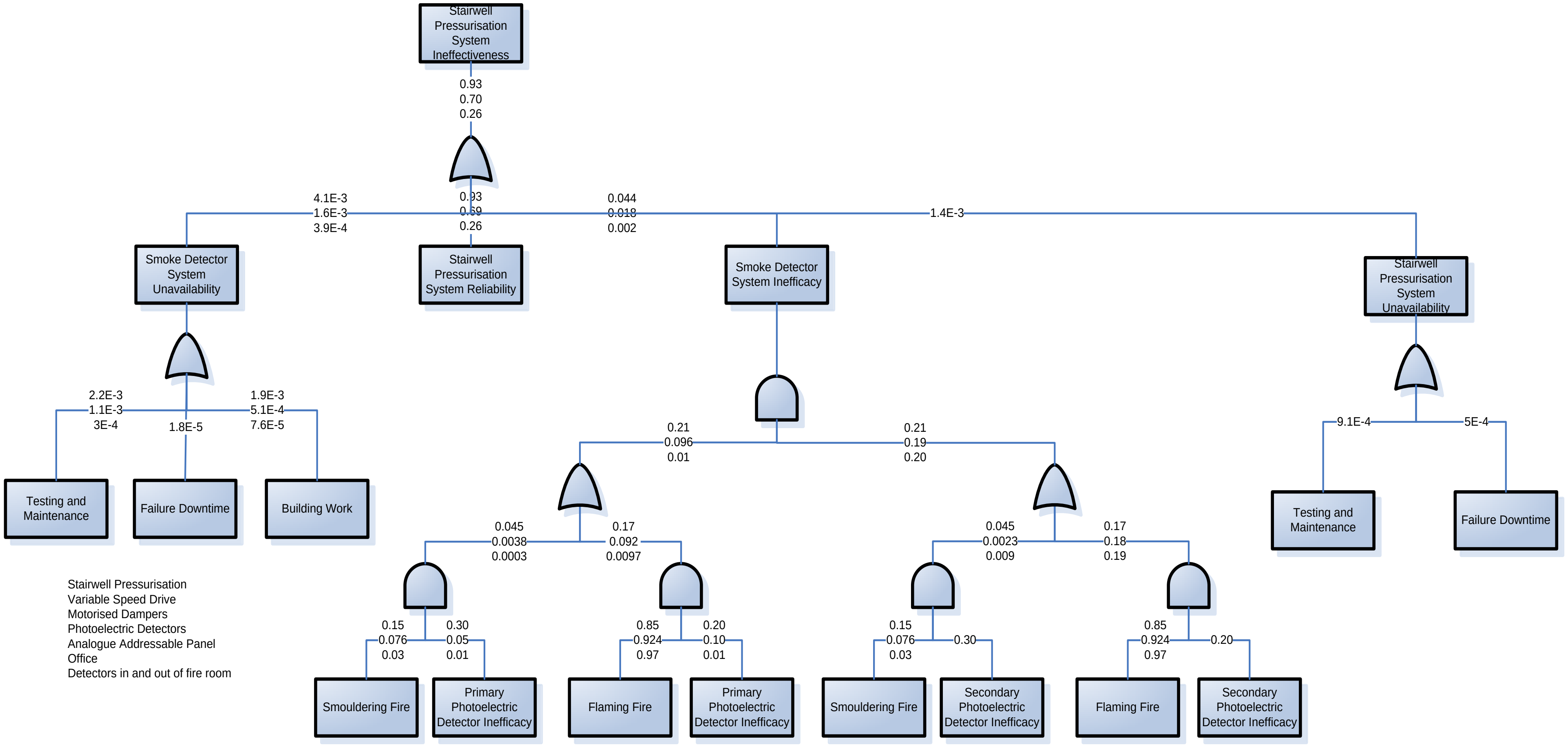
Stairwell Pressurisation (simple)
Photoelectric Detectors
Analogue Addressable Panel
Office
Detectors in and out of fire room

Figure C.22: Stairwell Pressurisation System Effectiveness Fault Tree



Stairwell Pressurisation
Variable Speed Drive
Photoelectric Detectors
Analogue Addressable Panel
Office
Detectors in and out of fire room

Figure C.23: Stairwell Pressurisation System Effectiveness Fault Tree



Stairwell Pressurisation
Variable Speed Drive
Motorised Dampers
Photoelectric Detectors
Analogue Addressable Panel
Office
Detectors in and out of fire room

Figure C.24: Stairwell Pressurisation System Effectiveness Fault Tree

Smouldering Fire Statistics

Proportion of fires which did not develop beyond smoulder - 2006/07 data

General Property Use Group Name	Smoulder only	Incident ID	Percent
Construction, Renovation	4	37	11%
Residential - Sleeping	1,284	3198	40%
Residential -Outbuilding	48	357	13%
Commercial, Retail, Manufacturing, Storage	387	1003	39%
Educational	85	207	41%
Health, Institutional	118	196	60%
Recreational, Assembly	65	204	32%
Communications, Research	7	17	41%
Rural, Farming, Forests	51	167	31%
Utilities, Disposal	7	23	30%
Transportation	18	41	44%
Water Areas	3	4	75%
Other	8	28	29%
Not Recorded	0	4	0%
Total	2,085	5,486	38%

Note: Based on the Termination Stage field. Options for this field are Overheat, Smoulderand Flame. Smoulder column above is a count of fires in the overheat and smoulder phase.

Appendix D

Sprinkler Survey Summary Statistics

Year	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**All Years**	**%**
Total surveys	53	112	73	83	124	163	272	288	124	1292	
# Offices	14	10	12	11	18	16	30	30	11	152	11.76%
# Apartment	1	0	2	2	3	7	8	11	8	42	3.25%
Faults/Issues											
Inadequate Supply	2	1	7	0	5	1	4	2	0	22	1.70%
Signalling Fault	1	0	4	1	0	1	3	3	1	14	1.08%
FSI	1	2	1	0	0	3	4	1	1	13	1.01%
Flow Switch	0	1	2	0	0	0	0	0	0	3	0.23%
Floor Isolation	0	1	0	0	0	0	0	0	0	1	0.08%
Street valve	0	2	2	0	1	1	1	1	0	8	0.62%
Pump performance	0	3	5	0	3	0	4	3	1	19	1.47%
Pump Start	0	2	1	1	3	2	2	4	1	16	1.24%
Sounders	0	1	1	0	0	0	0	0	0	2	0.15%
AIG	0	1	1	0	2	1	1	3	2	11	0.85%
Isolated	0	1	0	0	0	0	0	1	1	3	0.23%
Pressure switch	0	0	0	0	0	0	1	0	1	2	0.15%
Unprotected Areas	1	5	1	4	2	2	9	6	2	32	2.48%

Table E.1: Summary Statistics for Sprinkler Surveys for all Building Types 1999 – 2007

	Office		Apartment	
Faults/Issues	#	%	#	%
Inadequate Supply	3	1.97%	1	2.38%
Signalling Fault	2	1.32%	1	2.38%
FSI	1	0.66%	0	0.00%
Flow Switch	0	0.00%	0	0.00%
Floor Isolation	0	0.00%	0	0.00%
Street valve	6	3.95%	0	0.00%
Pump performance	4	2.63%	0	0.00%
Pump Start	5	3.29%	2	4.76%
Sounders	0	0.00%	0	0.00%
AIG	4	2.63%	0	0.00%
Isolated	1	0.66%	0	0.00%
Pressure switch	0	0.00%	2	4.76%
Unprotected Areas	3	1.97%	4	9.52%

Table E.2: Summary Sprinkler Statistics for Office and Apartment Buildings

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