FIRE CODE REFORM

Technical Report
FCRC-TR 98- 05

Reliability of Stair Pressurisation & Zone Smoke Control Systems

FCRC Project 4
Fire Safety System Design Solutions
Part A – Cure Model & Residential Buildings

Fire Code Reform Research Program
August 1998

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Background

The Fire Code Reform Research Program is funded by voluntary contributions from regulatory authorities, research organisations and industry participants.

Project 4 of the Program involved development of a Fundamental Model, incorporating fire-engineering, risk-assessment methodology and study of human behaviour in order to predict the performance of building fire safety system designs in terms of Expected Risk to Life (ERL) and Fire Cost Expectation (FCE). Part 1 of the project relates to Residential Buildings as defined in Classes 2 to 4 of the Building Code of Australia.

This Report was relevant to the project activities in support of the Model's development and it is published in order to disseminate the information it contains more widely to the building fire safety community.

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Comments

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NOMENCLATURE

FFCP	Fire Fan Control Panel
FIP	Fire Indication Panel
N_F	Expected Number of faults
p	Probability density function of failure
P_{CF}	Probability of component failure
R	Reliability
T	Maintenance Period
t_D	Expected down time
t_R	Time when repair is completed
t_{DF}	Time to detect fault
t_F	Time from the start to a fault occurs
dt_R	Time duration for repair

Glossary

Terms related to System:

Reliability	The probability that a system or a device will operate for a given period of time and under given operational conditions
Availability	The proportion of time that a system is available in a large time interval; it can also be expressed in terms of instantaneous availability, that is, the probability that a system will be available at any random time
Maintainabiliy	The probability that a device that has failed will be restored to operational effectiveness within a given period of time when the maintenance action is performed in accordance with prescribed procedures
Failure	The termination of the ability of an item to perform its required function
Partial Failure	Failure resulting from deviations in characteristics beyond specified limits but not such as to cause complete lack of the required function
Complete Failure	Failure resulting from deviations in characteristics beyond specified limits such as to cause complete lack of the required function

Terms related to Component:

Primary Failure	A primary failure is defined as the component being in the non-working state for which the component is held accountable, and the repair action on the component is required to return the component to the working state
Second Failure	A second failure is the same as a primary failure except that the component is not held accountable for the failure. Past or present excessive stresses placed on the component are responsible for the secondary failure.
Command Fault	A command fault is defined as the component being in the non-working state due to improper control signals or noise and, frequently, repair action is not required to return the component to the working state.

1. Aim

This investigation is to determine the reliability of stair pressurisation and zone smoke control sub-systems. The effectiveness of the sub-systems is not considered in this investigation.

2. Introduction

Stair Pressurisation Sub-System and Zone Smoke Control Sub-System are commonly used in high rise buildings. It has been well recognised that the major cause of death in building fires is smoke, and one of the most important functions of the fire safety system is to keep the exit route free of smoke. Stair pressurisation and zone smoke control sub-systems directly serves this purpose using the same principle, ie, using differential pressure to control the smoke movement. These systems will only be Operative if the detectors successfully detect the fire. Effectiveness of the system is defined as the product of the reliability of the system and the efficacy, that is,

$$Effectiveness = \mathbf{Re}\ libility \times Efficacy$$

where the efficacy is a measure of the degree to which it achieves the system performance given that the system is reliable. This is further illustrated in Figure 2.1.

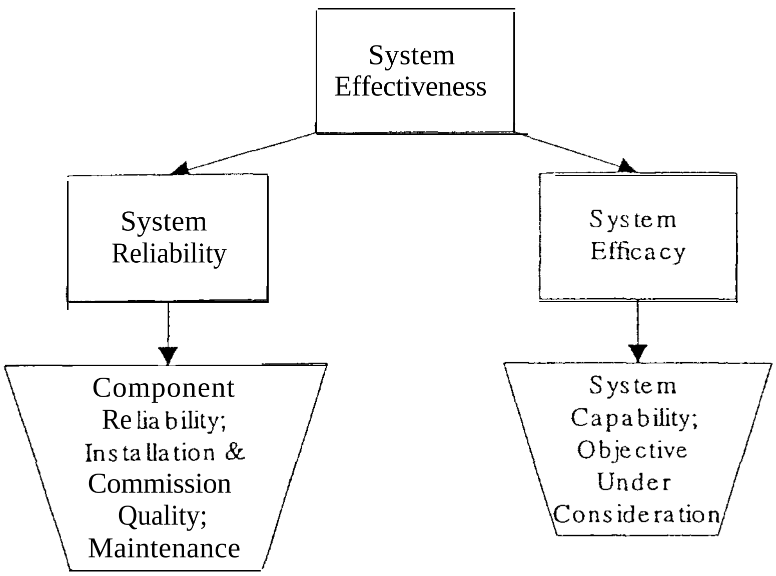

Figure 1: System Effectiveness

The success of the smoke management systems relies on both its reliability and efficacy. This document only deals with the reliability. Thus the probability of the final success of the smoke management systems is:

$$P_{Eff} = P_{RSM} \times P_{ESM} \quad (1)$$

where
P_{Eff} = Effectiveness of the smoke management
P_{RSM} = Reliability of the smoke management system
P_{ESM} = Efficacy of the smoke management system

To ensure that the stair is smoke-free, a minimum level of differential pressure must be maintained. Tests conducted by the CSIRO have demonstrated that air flows in excess of 0.3 m/s through a door will minimise the spread of smoke against the direction of flow. Accordingly, the Australian Standard adopted a minimum of 1 m/s [1]. On the other hand, excessive pressure difference can cause a large pressure force on the stair door which will give difficulty for people to open during evacuation. Thus, in the design of the stair pressurisation sub-system, both criteria, that is, the pressure difference to preventing smoke spreading into the stair and the maximum force required to open the door, must be satisfied. The Australian Standard requires the maximum force to open the door being 110 N [1].

In order for the Stair Pressurisation Sub-System operate effectively, different designs such as multi-fans or variable speed fans may be used. The reader is referred to [2] for details. This investigation considers the reliability of a single fan sub-system only. A description of the single fan sub-system will be given in subsequent sections.

There are also many different types of Zone Smoke Control Sub-System. The principle of this sub-system is the same as for the Stair Pressurisation Sub-System, ie, using differential pressure to control the smoke movement. In a Zone Smoke Control Sub-System, pressure difference between the fire floor and the other floors is created by fans and dampers such that the other floors have a higher pressure than that of the fire floor, thus preventing smoke migrating into the other floors; at the same time, smoke is extracted from the fire floor so that the smoke level on the fire floor is reduced as well. A description of this sub-system will be given in subsequent sections.

3. Methodology

3.1 Introduction

Reliability is defined as "the characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time" [3]. The probability of failure is then 1 minus reliability.

Reliability of the system depends on a number of factors which include component failure rate, human errors, quality of commissioning, maintenance level, component arrangement within the system (serial or parallel). Using a crude estimation, the reliability of a new smoke management sub-system that has not been commissioned and made up of only 2 HVAC system fans (whose primary function is heating, ventilation and air conditioning) and 9 other components is estimated as 0.565 using a reliability cf G.99 for a HVAC fan and 0.94 for other components as suggested by Klote et al. [2]. This means that this system has a probability of failure of 0.23. A commissioned system will have a higher reliability depending on commissioning quality. The reliability of a non-commissioned system is dependant on the correct installation of components and their working condition. The reliability of a commissioned system is dependant upon the life of the components and routine testing and repair after commissioning. In this investigation, quality of commissioning is considered.

Fault trees are the standard method for reliability analysis. Figure 2 shows fault trees for two events A and B. There are two most common combinations, OR and AND. The OR function describes Event A occurring when either Event B or Event C (Figure 2) is realised. The AND function describes Event A occurring when both Event B and Event C are realised. Symbols used in the fault trees are shown in Figure 3.

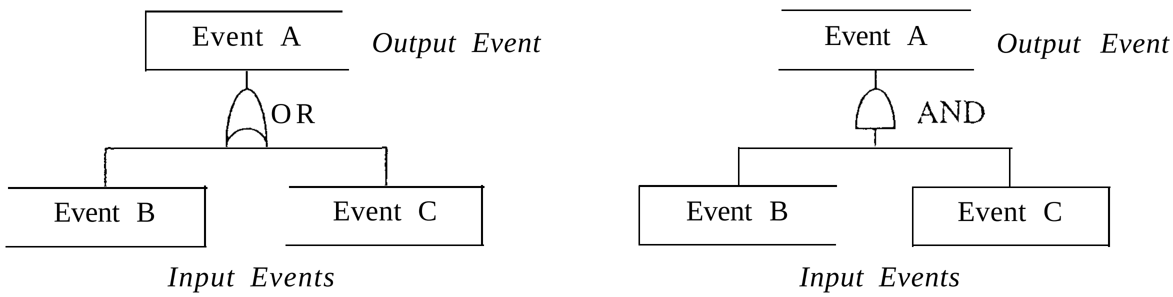

Figure 2: Two event fault trees, OR and AND respectively

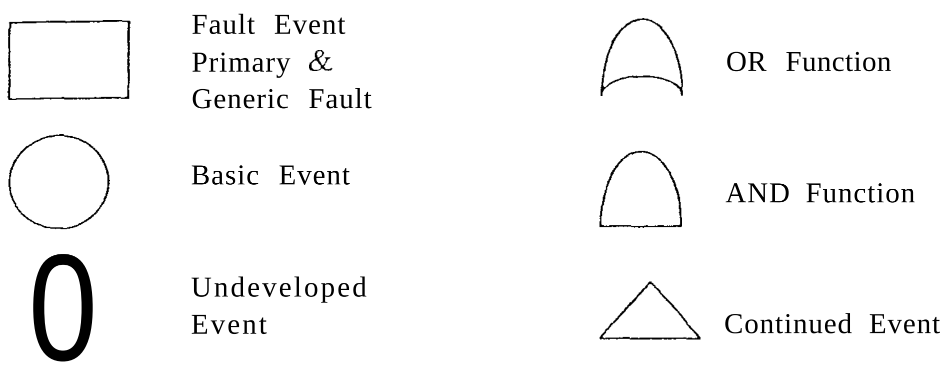

Figure 3: Symbols Used in Fault Trees

3.2 Type of Component Failure

Component failures are classified as either primary failure, second failure or command faults.

A primary failure is defined as the component being in the non-working state for which the component is held accountable, and the repair action on the component is required to return the component to the working state [4]. The primary failure occurs under inputs within the design envelop. and component natural aging is responsible for the failure. For example, “tank rapture due to metal fatigue” is a primary failure.

A second failure is the same as a primary failure except that the component is not held accountable for the failure. Past or present excessive stresses placed on the component are responsible for the secondary failure. These stresses involve out of tolerance conditions of amplitude, frequency, duration, or polarity, and energy inputs from thermal, mechanical, electrical, chemical, magnetic, or radioactive energy sources. Examples of secondary failures are “fuse is opened by excessive current” and “earthquake crakes storage tanks”. When the damage failure mode for a primary or second failure is identified, and failure data is obtained, primary and second failure events are the same as basic failures.

A command fault is defined as the component being in the non-working state due to improper control signals or noise and, frequently, repair action is not required to return the component to the working state. Examples of command faults are "power is applied, inadvertently, to the relay coil", "switch randomly fails to open because of noise".

Failure of one component of the system may result in a complete failure of the system. For instance, the failure of the supply air fan can cause the complete failure of air supply to the building if there is only one supply air fan in the system. In some cases, the failure of one component may not have any significant effect to the system. For instance, if a damper on a remote floor (far away from the fire floor) fails to function properly, the smoke extraction system will work properly but less effective. A failure of more than one damper on remote floors may lead to a partial failure of the system.

In this study, all failure types are not distinguished from one another. The rate of failure is the overall value for the all failure types, ie. primary failure, second failure and command fault. Failure of the system, however, has two types, ie, complete failure and partial failure.

3.3 Installation, Commissioning and Maintenance

Installation fault is considered to be due to human error. According to Lees [5], the probability of installation fault P_I is 0.1. Gibson et al. [6] used 0.001 to 0.01, however, this is considered to be too low as suggested by Moore et al. [7] after holding discussions with design engineers.

There is usually a standard procedure for the commissioning which is often undertaken or supervised by professional engineers. It is thus expected that the probability of error for the items not embedded in the commissioning procedure is low. In the worst case, this probability of commissioning fault Pc equals to the probability of installation fault Pi. Lees [5] quoted a value of 0.003 while Gibson et al. [6] indicated a value of 0.01. Corrective action will be given if any fault is found during the commissioning phase. With a lower installation and commissioning quality, the correction phase will take a longer time. But a properly commissioned system can be assumed to be in working order.

Maintenance is important for fault detection, particularly for those components which are not used as part of daily life use, which is the case for most part of the fire safety system. In some cases, maintenance is the only means to detect a fault.

The level of maintenance is another important aspect in the assessment of the reliability of the system. Australian Standard 1851 Part 6 [7] classified the maintenance into four levels as follows:

- Level 1: consist of functional checks by means of sensory inspection such as sight, touch, hearing or smell.
- Level 2: consist of Level 1 plus cleaning, lubrication, simple routine maintenance and adjustment which does not necessitate taking the equipment out of service.
- Level 3 consist of Level 2 plus testing and measurements as necessary to ensure optimum effective performance. These routine may require equipment to be taken out of service, but will generally enable rapid reinstatement if the need arises.
- Level 4: consist of overhaul and test procedures which will normally necessitate an item being taken out of service, possibly for prolonged period.

The Australian Standard further defines the frequency to be applied for various components for each level. A summary of some components which will be used in this analysis is given in Table 2. The Standard further states that where a Level 1 inspection indicates a malfunction of any sort, appropriate action at Level 2, 3 or 4 shall be initiated immediately regardless of the timing for the selected action in the **maintenance schedule.** Detailed instructions of each level of maintenance of various components are also provided. For instance, Level 1 maintenance of fan includes

- check bearing for noise and overheating
- check fans for emissive vibration
- check guards and other safety features for satisfactory condition
- check fan belts for wear
- check flexible connections, where fitted, for leaks, tearing or fraying

In most cases, if Level 1 is carried out properly, faults can be detected; and once a fault is detected if subsequent actions are taken as required by the Australian Standard, then the system can return back to normal conditions. However the detection of faults highly depends on the quality of the maintenance worker. A sensitivity study of the quality of maintenance on the system reliability will be given. Maintenance of the system is assumed to have been appropriately carried out according to the Australian Standard 1851.5 [7].

Table 2: Frequencies for Maintenance (according to Australian Standard 1851)

Item	Level 1	Level 2	Level 3	Level 4
Supply and return air fan	Monthly	Quarterly	Yearly	Only if inspection indicates necessity
Smoke-spill or air pressurisation fan	Quarterly	Half-yearly	Two-yearly	Only if inspection indicates necessity
Fire mode air dampers for smoke spill fresh air and recycle air	Half-yearly	Yearly	N/A	Only if inspection indicates necessity
Fire isolated escape routes protected by air-pressurisation system	Monthly	Yearly	Two-yearly	Only if inspection indicates necessity

3.4 Time to Detect a Fault

Component reliability is usually expressed using a exponential function

$$R(t) = e^{-\lambda t} \tag{2}$$

where R(t) is the reliability of the component at time t, λ is the failure rate. The failure **density function is**

$$p(t) = \frac{d(1-R(t))}{dt} = \lambda e^{-\lambda t} \tag{3}$$

Thus the mean time to failure within the maintenance period of T is

$$t_F = \frac{\int_0^T tp(t)dt}{\int_0^T p(t)dt} = \frac{-Te^{-\lambda T} + 1/\lambda(1-e^{-\lambda T})}{1-e^{-\lambda T}} = \frac{1}{\lambda} - \frac{Te^{-\lambda T}}{1-e^{-\lambda T}} \tag{4}$$

The time to detect a fault depends on the use of the component. In the case where the component is part of the daily life use, for instance power system, it is expected that the fault which leads to the failure of the system will be detected in a short time, in many cases immediately. The corrective action will also be given promptly. The down time of the system is expected to be short which is usually in hours not days.

If the component is not part of the daily life use systems, it is unlikely that a fault can be detected until the maintenance time. Thus the mean time to detect a fault t_{DF} for a component which is not part of daily life use is the maintenance time T subtract the mean time to failure in the maintenance period, ie

$$t_{DF} = T - t, \qquad (5)$$

3.5 Expected N-umber of Faults

Assumed that no repair is given prior to the maintenance time, the expected number of faults for one component is the same as the accumulated probability of failure, ie

$$N_F = 1 - R(t) = \int_0^T p(t)dt = 1 - e^{-\lambda T} \qquad (6)$$

where N_F is the expected number of failure of one component within one maintenance period T. When λT approaches to zero, $N_F = \lambda T$.

When one repair is given at time t_F, and finished at t_R, the expected number of faults or the accumulated probability of failure during one maintenance period T is

$$N_F = \int_0^{t_R} \lambda e^{-\lambda t} dt + \int_{t_R}^{T} \lambda e^{-\lambda(t-t_R)} dt = 2 - e^{-\lambda t_R} - e^{-\lambda(T-t_R)} \qquad (7)$$

where

$$t_R = t_F + dt, \qquad (8)$$

where dt_R is the time required for the repair, and t_F is given by equation (4).

3.6 Expected Down Time

The expected down time for the component is the expected time duration when the component is not in normal operational condition. For a components of a daily life use, this time is

$$t_D = N_F \times dt, \qquad (9)$$

For a component which is not part of daily life use, the fault is not likely to be detected until to the time of maintenance, thus the down time is

$$t_D = N_F \times (t_{DF} + dt_R) = N_F \times ((T - t_F) + dt_R) \qquad (10)$$

3.7 Mean Probability of Failure

The mean probability of failure of any component is the time when the component is in fault over the total time of concern. The total time is chosen to be the time of one maintenance period. Therefore

$$P_{CF} = \frac{t_D}{T} \tag{11}$$

where P_{CF} is the mean probability of component failure. The mean component reliability is $1-P_{CF}$.

4. Component Reliability

4.1 Power Failure

In most cases, backup batteries are installed. The failure rate for the mains was quoted by Steciak et al. [9] as being 4.75 x 10^{-6}/hr. Since power is part of daily use, a detection time of power failure is immediate and the repair time is usually in hours not days. Assuming that the maintenance time is 4 weeks, the number of faults in one maintenance period is 4 × 7 x 24 x 4.75 x 10^{-6} =3.192 x 10^{-3}. Assuming that the repair time is 12 hours, the total down time is 0.0383 hours. This gives the reliability of 1-0.0383/(4 × 7 × 24) = 0.999943 or a probability of failure of 0.000057. This agrees well with the 140 Williams Street Project [10] in which a probability of failure of 0.00005 was used.

The mains power often has back-up batteries and/or power generators. This redundancy will further reduce the probability of system failure due to power failure. Hence it can be concluded that the failure of a fire protection system due to power failure is very unlikely. Such a small probability of failure is considered to be negligible.

4.2 FIP or FFCP Fault

The failure rate of FIP or Fire Fan Control Panel (FFCP) is 8.5 × Since the FIP or FFCP panel is not part of daily life use equipment, it is unlikely that a fault will be detected until the maintenance time. Using equation (4), the mean time to detect a fault is approximately half of the maintenance period which, according to AS 1851.8 [11], is 30 days. Using equation (6) the expected number of faults during one maintenance period is 6.12 × 10^{-3}. The expected down time is 2.203 hours using equation (IO), and the mean probability of failure for FIP or FFCP is 0.00306.

4.3 Detector Fault

The failure rate for a detector was given by Steciak et al. [9] to be 1.2 x 10^{-6} per hour. Using equations (10) and (11) and further assuming that the repair time dt_R is much shorter than t_{DF}, for T = 30 days, the probability of failure is 0.000432.

4.4 Connection Fault

The connection fault between FIP and FFCP or between FFCP and fans or dampers is assumed to be 1.2×10^{-6} per hour as quoted by Steciak et al. [9]. Thus the probability of failure for connection is also 0.000432.

4.5 Fans

The failure rate of fans was indicated by Gibson et al. [6] as 2×10^{-4} per hour. Using this value the expected number of faults during one maintenance period, ie monthly Level 1 maintenance, is 0.139 *(30* days per month is assumed). Since fans are used for normal HVAC operation, a prompt corrective action can be assumed. Assuming that the repair time is one day per repair, the mean probability of failure of the fan is 0.139/30 = 0.00363.

4.6 Dampers

4.6.1 Probability of Failure (Operation)

The rate of failure (operation) is 0.001 faults per day according to Lees [5]. It is unlikely to detect a fault (unoperational) until the maintenance time unless the damper fail to remain open in the normal HVAC condition.

Using equation (4), t_F is 12.4 weeks for T = 26 weeks. The mean reliability is 0.914, ie. a mean failure probability of 0.0857 using equation (1 1).

4.62 Probability of Failure (remain to open)

The failure rate for unable to remain open is 0.0001 faults per day according to Lees [5]. This indicates that there will be 0.0180 faults for T = 26 weeks (182 days). If the damper is part of daily life use system and in the normal operational mode the damper is required to remain open, then this type of fault can be easily detected and a prompt fix can also assumed. For instance, a supply air damper at any floor is required to be open during the normal HVAC operation. If the supply air damper is closed, the people on the floor can quickly detect that there is something wrong with the HVAC system. Assuming that the time to detect and fix is 2 days, then the probability of the damper in fault is 0.0002 for T = 26 weeks. This indicate that a mean reliability of the damper (remain to open) of 0.9998. The assumption of 2 days to fix is probability conservative. In reality, for some buildings, windows are not openable, the repair usually takes hours rather than days. Nevertheless this is unlikely have any significant impact on the overall assessment of the reliability of the system as this will reduce further the probability of failure which is already very small.

4.7 Sensitivity Analysis

This analysis assumes that all faults will be detected during Level 1 maintenance. This may not be true in practice which depends on the skill of maintenance personnel and management quality. A sensitivity analysis is conducted and the reliability of a fan is tabulated in Tables 1 and 2.

Table 1: Reliability of Fan vs. Maintenance Quality (Assuming Repair Time = 1 Day)

Detect Faults	Reliability
100% Level 1	0.9952
75% Level I & 25% Level 2	0.9923
50% Level 1 & 50% Level 2	0.9904
25% Level 1 & 75% Level 2	0.9880
0% Level I & 100% Level 2	0.9856

Table 2: Reliability of Fan vs. Maintenance Quality (Assuming-Detecting Fault Probability of 50% Level 1 & 50% Level 2)

Detect Faults	Reliability
48 Hours	0.9808
24 Hours	0.9904
12 Hours	0.9952
6 Hours	0.9976
2 Hours	0.9992

Klote and Milke (1992) reported that the reliability of a non-commissioned fan of 0.99. This indicates that the average quality of maintenance is in the upper half of Table 1 and/or the average time to repair a fault is in the lower part of Table 2 since the reiiability of a commissioned fan is higher than that of a noon-commissioned fan. Therefore 0.995 is used in this analysis.

5. Reliability of Stair Pressurisation Sub-System

5.1 System Layout

This stair pressurisation sub-system has fewer components than the Zone Smoke Control Sub-System. A typical component layout is shown in Figure 4. In a single fan system, air is supplied by the fan which is usually located at the top or the bottom of the stairwell. The air is injected from the top of the stairwell, or in the case of a building with more than eight stories multiple injection points are recommended. This air flow is regulated by the air damper before supply air fan. Both fan and dampers receive signal from the Fire Fan Control Panel (FFCP) which can be part of the Fire Indicate Panel (FIP).

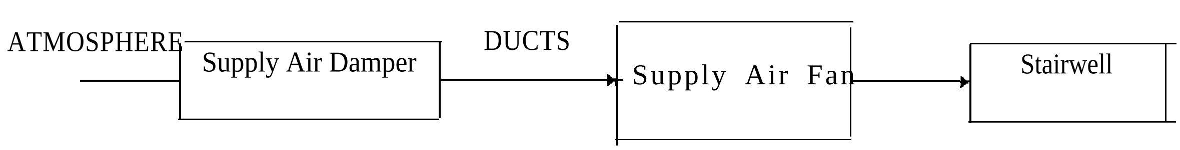

Figure 4 Schematic Layout of the Stair Pressurisation Sub-Systems.

5.2 Fault Tree

An fault tree as shown in Figure 5.1 is used for the overall system reliability analysis. As can be seen, the system will fail if one or more of the followings occur

- Power fails
- No signal received by fans and dampers
- Fan does not function properly
- Damper does not function properly

Fault tree analysis for each of the above components will be given in Sections 5.3 to 5.6. Details follows.

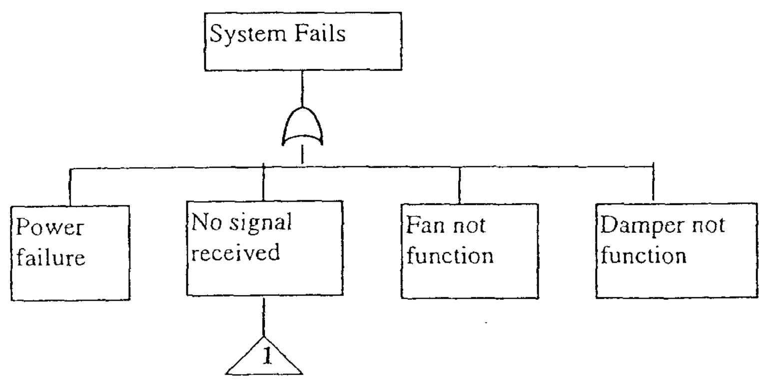

Figure 5: System Fault Tree (Level 1)

5.3 Probability of No Signal Received by Fan or Damper

This section calculate the probability of no signal received by fans and dampers given that the mains power is function- For fans and dampers to receive signal, the following conditions must be satisfied:

- Detectors issue a signal
- Signal send to FIP
- FIP is reliable
- Connection from FIP to FFCP is reliable
- FFCP is reliable
- Connection from FFCP to fans and dampers is reliable

In conclusion, the probability of no signal received by fans and dampers is 0.008 1. This analysis assumes that the automatic smoke detectors for the Zone Control System are installed and of the required type according to AS 1668.1 [1]. Further it is assumed that there is no sprinkler system or smoke detection system in the building. In case where a sprinkler system or a smoke detection system is installed, the Zone Smoke Control System can be activated by the activation of the sprinkler system or the smoke detection system. This additional activation mechanism will have a positive effect on the reliability of overall system, however only to a insignificant degree. Assuming that the probability of FIP receiving a signal is 1, the probability of no signal received by fan or damper is 0.008104.

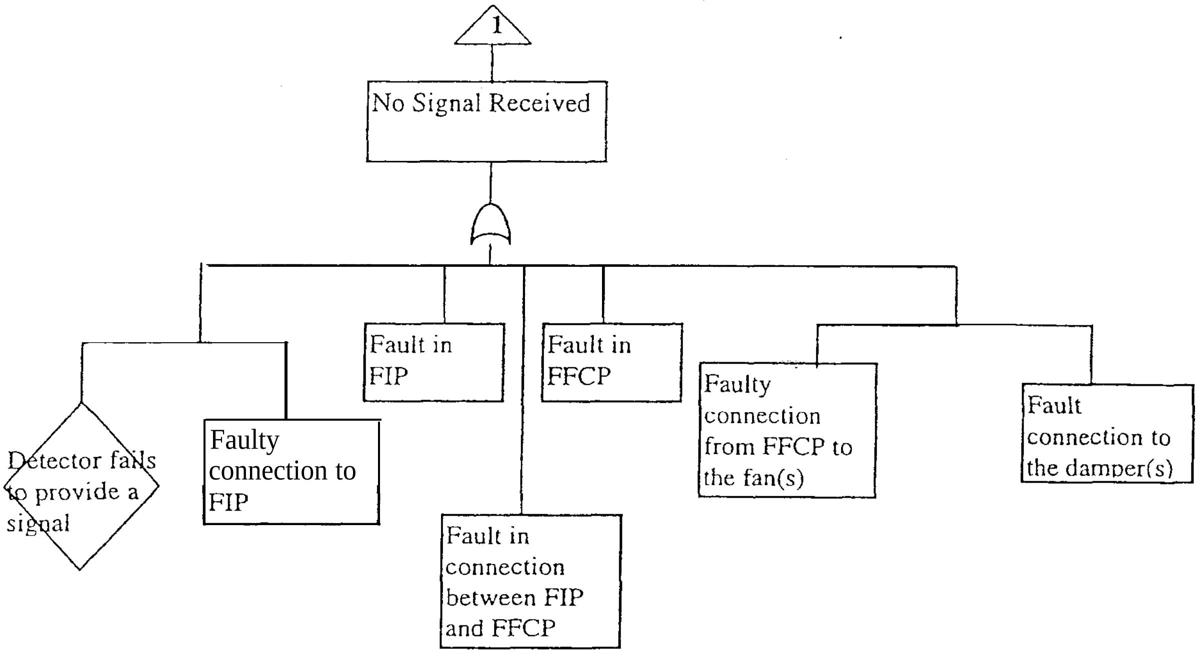

Figure 6: Fault Tree for the Fans or Dampers Not Receive Signal

5.4 Reliability

The reliability of the Stair Pressurisation Sub-System is 0.90 using the fault trees given in Figures 5 and 6.

6. Reliability of Zone Smoke Control Sub-System

6.1 System Description

The fans used in the majority of the sub-systems are part of the HVAC Sub-System. The return air fan can be used as the smoke spill fan if the return air fan satisfies the requirement for the smoke spill fan: In the case of fire, the return air damper is closed so that there will be no smoke recirculated back into the building, the supply air damper on the fire floor will be closed, and the return air damper is open so that smoke can be extracted out from the fire floor. On the other floors, the supply air dampers are open and the return air dampers are closed such that these floors will have a higher pressure than that of the fire floor. The smoke spill fan will be turned on, and the external air damper will be open, thus smoke are extracted out of the building. This operation is tabulated in Table 1. A typical component layout of the sub-system where the plant room is above the spaces being served is shown in Figure 5. When the plant room is below the spaces being served, the smoke spill damper will be in different operation modes, typically being open when there is no fire and closed when there is a fire. This difference will have little impact on the reliability analysis. For the purpose of this study, the plant room above the spaces being served is considered.

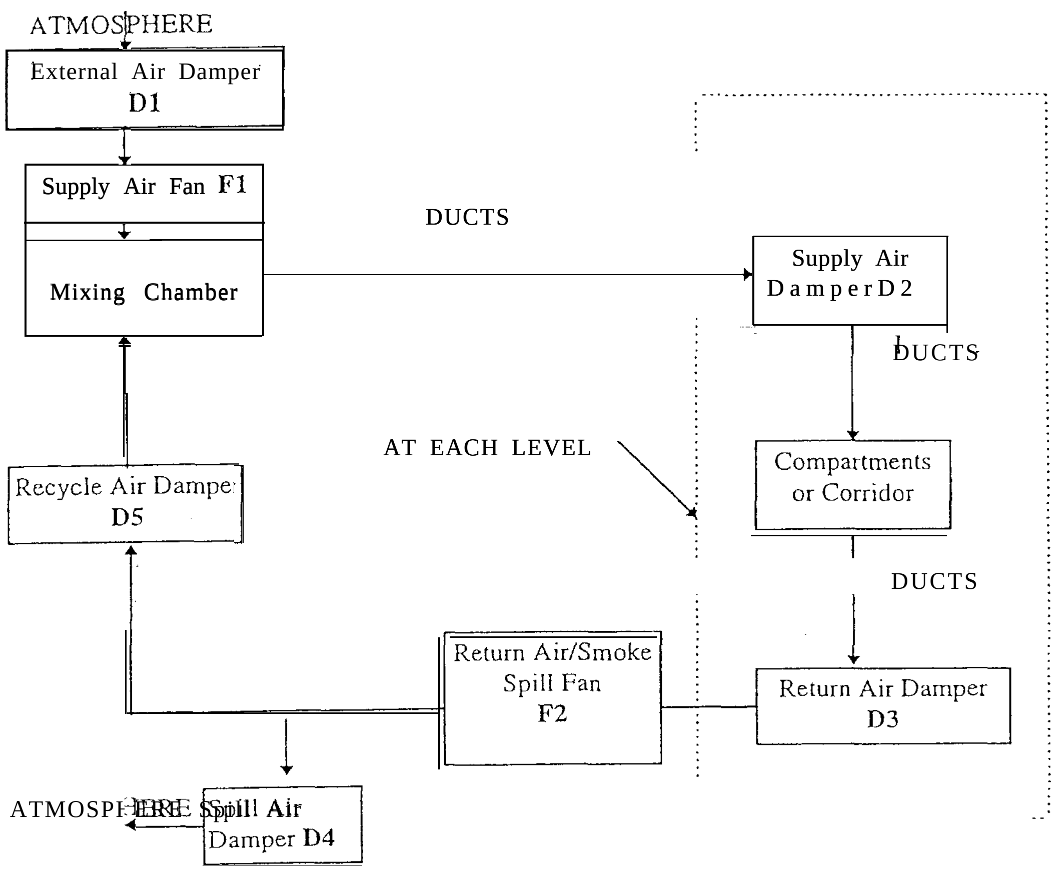

Figure '7: Schematic Layout of the Zone Smoke Control Sub-System -Typical Installation with Plant Room above Spaces Being Served

Table 3: Component Positions According to Mode of Operation for Zone Smoke Control Sub-System

		Supply Air Fan **F1**	Return Air/Smoke Spill Fan **F2**	External Air Damper **D1**	Supply Air Damper D2	Return Air Damper **D3**	Spill Air Damper **D4**	Recycle Air Damper D5
Normal Operation		On	On	Open	Open	Open	Closed	Open
In the case of Fire	a. Level of Fire Origin	On	On	Open	Closed	Open	Open	Closed
	b. Levels of non Fire Origin				Open	Closed		

6.2 System Failure Due to Damper Failure

6.2.1 Introduction

The unopertional failure rate of motorised dampers is 0.001 faults per day and the failure rate of unable to remaining open is 0.0001 faults per day according to Lees (1986). In the normal HVAC condition, all dampers on all floors are open, the smoke spill damper is closed, the recycle air damper is open so that the return air will be mixed with the supply air. The outside air damper maybe open or closed or partial open. In the event of fire, supply air damper on the fire floor is closed, and the return air damper remains to be open. On the other levels, supply air dampers remains to be open and the return air dampers to be closed. The recycle air damper will be closed and the exhaust air damper open. This is illustrated in Figure 8 in which the external air damper is assumed to be open in the normal operational condition and in the event of fire.

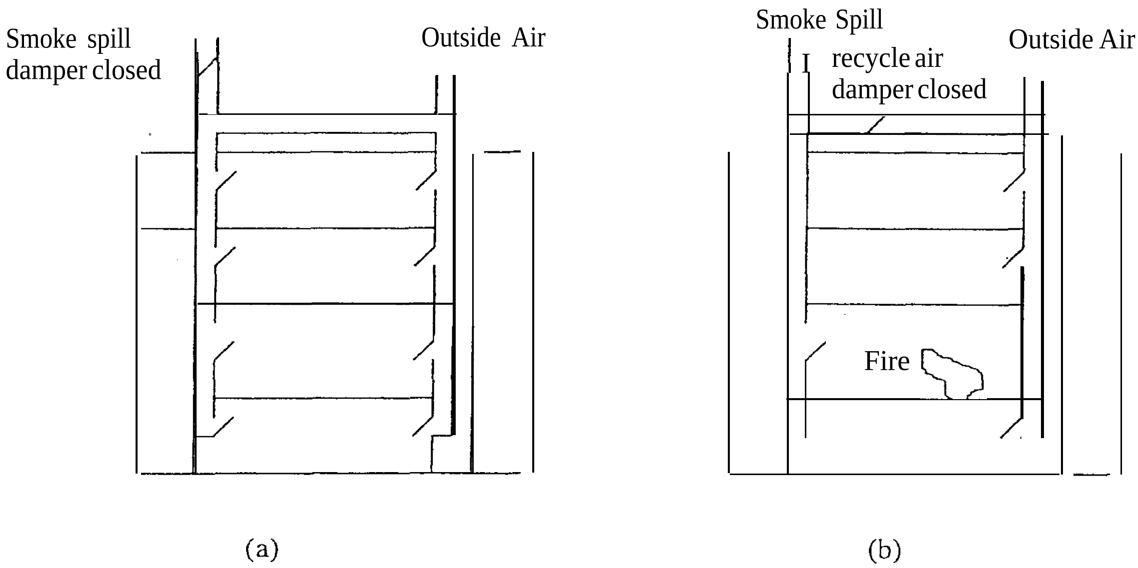

Figure 8: Dampers Positions(a) Normal HVAC and (b) In the Event of Fire

To create a minimal pressure differential to preventing the migration of smoke from the fire floor to the other **floors,** the following conditions must be satisfied:

- the supply air damper on the fire floor must be closed;
- the return air damper on the fire floor remains to be open;
- the recycle air damper must be closed
- the exhaust air damper must be open.

The operation of dampers on other floors will also affect the performance of the Zone Smoke Control System. A minimal number of dampers need to be operational such that the pressure differential is large enough to preventing the smoke migration from the fire floor to the other levels. This minimum number can be estimated by analysing flow conditions using program such as ASCOS [2] for a particular design. A complete reliable system has no component failure. For this study, it assumes that if other components in the system are reliable, the return air dampers have the following effect on the system:

For a system has more than 10 floor levels,

- If greater than **20%** return air dampers fail to be closed, the system has a complete failure.
- If less than or equal to 20% but greater than 10% of return air dampers fail to be closed, the system has a partial failure.
- If less than 10% of return air dampers fail to be closed, the system is likely reliable.

For a system has less or equal to 10 but greater 5 floor levels,

- If more than 2 return air dampers fail to be closed, the system has a complete failure.
- If 2 return air dampers fail to be closed, the system has a partial failure.
- If only 1 return air dampers fail to be closed, the system is likely reliable.

For a system has less or equal to 5 floor levels,

- If **more** than 1 return air dampers fail to be closed, the system has a complete failure.
- If 1 return air dampers fail to be closed, the system has a partial failure.
- If no return air dampers fail to be closed, the system is complete reliable.

Note that all the above assumptions about the return air dampers are the return air dampers on the other floors which exclude the return air damper on the fire floor.

For the supply air dampers, the requirement for the zone control purpose is for them to remain to be open. It is unlikely that they will be closed because fire is only a short period of time. If during normal HVAC condition, any of the supply air dampers is closed, it will be immediately detected, and a prompt fix can also be assumed. Thus the failure of the supply air dampers can be neglected.

This conclusion is also applicable to the return air damper. If during normal HVAC condition, a return air damper is closed, it will also be immediately detected. A prompt fix can also be assumed.

6.2.2 Probability of System Failure Due to Damper Failure

As discussed, if any one of the followings occurs:

- the supply air damper on the fire floor fails to close or
- the return air damper fails to remain open or
- the recycle air damper fails to close or
- the exhaust air damper fails to open

the system will fail. According to the analysis in the previous sub-sections, the probability of damper failure (operation) is 0.0857 and probability of failure (remain open) is 0.0002. Thus the probability of failure of the system due to above failure modes for the Zone Smoke Control System is 0.2357 This failure analysis has not included failures due to dampers other than the four dampers listed (supply air damper, the return air damper on the fire floor, the recycle air damper and the exhaust air damper).

To account the system failure due to failure of the other dampers, the total number of floors need to be known. The probability of failure due to damper failure is tabulated for 5, 10 and 20 storey buildings in Table 4.

Table 4: The Effect of Damper on the Reliability of System

No. of Floors	Complete Reliable	Likely Reliable	At Least Partial Reliable	Complete Failure	Likely Failure	Partial Failure
5	0.534	0.534	0.734	0.466	0.466	0.266
10	0.341	0.629	0.737	0.659	0.371	0.263
20	0.139	0.613	0.718	0.861	0.387	0.292

6.3 Reliability

Using the fault trees as shown in Figures 5 and 6, the reliability of the Zone Smoke Control System can be obtained. The reliability values are tabulated in Table 5.

Table 5: The Reliability of the Zone Smoke Control System

No. of Floors	Complete Reliable	Likely Reliable	At Least Partial Reliable	Complete Failure	Likely Failure	Partial Failure
5	0.527	0.527	0.724	0,473	0.473	0.276
10	0.336	0.621	0.727	0.664	0.379	0.273
20	0.137	0.605	0.709	0.863	0.395	0.291

As can be seen, the Zone Smoke Control System has a probability of likely reliable of between 0.52 to 0.62 for a 5 to 20 storey building and a probability of at least partial reliable of approximately 0.72.

7. Conclusions

The reliability of Zone Smoke Control Sub-System and Stair Pressurisation Sub-System have been obtained using fault tree analysis.

Installation, commission quality are important factors. This analysis assumes that the system has been correctly commissioned. Thus the new system immediately after the commissioning has a reliability of one.

Maintenance has a significant effect on the reliability of the system. Particularly for the components which are not part of daily life use, in which case fault will usually not detected until the maintenance time. Sensitivity study shows that the quality of maintenance is as important as the frequency of the maintenance.

Dampers have been found to be the most unreliable component in both the Stair Pressurisation and Zone Smoke Control Sub-Systems. Improving the reliability of dampers via improving the quality of the dampers or reducing the maintenance period or alternatively reducing the number of dampers used in the system will all increase the reliability of the overall system. Alternatively providing redundancy to the dampers can also significant increase the system reliability.

In the Zone Smoke Control System, not all dampers have the same importance. The mix air damper and the exhaust air damper are considered to be most important. This conclusion is for the design analysised in this study. In some designs, the external air damper has the same importance.

This analysis is only part of the analysis of the effectiveness of the systems which is a function of both reliability and efficacy. The efficacy will depend on design quality and the use of the system. For instance, if the number of stair doors can be controlled during the evacuation, usually through a planed evacuation, the stair pressurisation system will generally effective given it is reliable. On the other hand, if more doors are open during the evacuation than what the system was designed for, the system will not be effective even when the system is reliable. This will be further discussed in the CESARE-RISK model.

It should be also aware that both Zone Smoke Control Sub-System and Stair Pressurisation Sub-System can be designed in different ways. Whilst the methodology presented in this reliability analysis may be used for other designs, the reliability values obtained in this investigation are only applicable to the designs investigated.

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