FACTORS AFFECTING THE RELIABILITY OF SPRINKLER SYSTEM IN AUSTRALIAN HIGH RISE OFFICE BUILDINGS

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ABSTRACT

A fault tree analysis (FTA) of the sprinkler systems for large high-rise office buildings is being carried out to determine the reliability of systems in Australia. This analysis is particularly intended to provide information on the sensitivity of the reliability to various factors in the building operations such as, rate at which tenancy changes occur, monitoring of valves and back up batteries, maintenance procedure etc.. To determine probabilities of the occurrence of various sprinkler system components failure, a comprehensive survey is being conducted involving a number of Australian high-rise office buildings (in this paper data from nine buildings are presented). In addition, data from overseas surveys has also been considered based on their relevance to the office buildings being considered. In this paper the analyses are confined only to wet-pipe systems, as these constitute the vast majority of automatic sprinkler systems in Australia and New Zealand. To develop the fault trees, the designs found in usual practice are considered, rather than the designs just complying the Australian codes with the minimum requirements. Analysis shows that sprinkler systems for high-rise office buildings in Australia are likely to be more reliable than that indicated by recent US store and office fires statistics. The difference may be attributable to the wet-pipe only system and stringent maintenance requirements by Australian regulations. Sprinkler zone shut off during tenancy changes appears to be the main factor that may lead to a sprinkler system failure.

KEYWORDS: Sprinkler, Reliability, Effectiveness, Survey, Tenancy change, Failure rate, Probability

INTRODUCTION

Water is supplied to automatic fire sprinklers (or *sprinkler heads*) throughout a system of piping, and are arranged so that they are able to automatically distribute sufficient water directly to a fire to extinguish it or hold it in check until fire fighters arrive [1]. This is achieved by cooling the fire and wetting surrounding materials in order for it to harder ignite. As a consequence of this application of water, there have been cases where the water interferes with the combustion process sufficiently to reduce the size of the fire and possibly extinguish it.

The effectiveness of a fire-safety system can be considered as the product of its *efficacy* and its *reliability* [2]. A research program [3] was undertaken to evaluate the *efficacy* (the degree to which a particular system achieves an objective, e.g. control or extinguishment of a fire, given that it operates) of a sprinkler system in an office building. It was found that when small office fire occurs, the fire is suppressed almost instantly. In all open-plan office fire tests, sprinklers had no trouble in containing the fire, especially above the desk where it was adjacent to fire initiation point. Furthermore, fire did not spread to adjacent workstations or associated combustibles.

During the time of automatic operation of the sprinklers, occupants of an open plan office area of similar dimensions did not suffer any significant distress or permanent harmful effects, provided they were not involved in the ignition and were reasonably mobile. The structure of the building was not damaged during the tests and carried the required loads without any signs of excessive deflection or other distress. The structural steel members and the composite floor slab suffered no measurable permanent deflection and would not have required any form of major repair before reoccupation if fire sprinklers had been incorporated in a typical office building.

Having established the efficacy of typical sprinkler systems experimentally, the purpose of the fault tree analysis herein is to estimate the *reliability* of a sprinkler system in a high-rise office building (60 storeys). The *reliability* of a sprinkler system is defined as the likelihood that it operates[*] and delivers the designed amount of water to the fire. In this paper, the analyses are confined to the wet-pipe systems as the vast majority of automatic sprinkler systems in Australia and New Zealand. Wet-pipe systems are installations in which the sprinkler piping network is permanently charged with water under pressure and are therefore suitable for use in buildings in which freezing never occurs [6].

DESCRIPTION OF AUTOMATIC SPRINKLER SYSTEM IN A TYPICAL HIGH RISE BUILDING

Water Supply

According to Building Code of Australia [7], a building over 25 m of height is required to have Grade 1 water supply of AS 2118.1-1999 [8] for the sprinkler system. Water supply from two separate mains is mostly used for the high-rise buildings in Australia and New Zealand. Strictly, this requirement is difficult to meet and sometimes a concession is given, such as mains passing along two parallel streets being considered as separate mains although strictly, they may not be entirely independent. Alternatively, an automatic pump supply from private reservoirs (mainly located in the basement) and two elevated private supplies (mainly located in the rooftop) is also widely used.

According to AS 2118.1-1999 [8], an office building requires a light hazard sprinkler system with fast response sprinkler heads at about 4.6 m maximum spacing. The design criteria for a light hazard sprinkler system dictates that the water supply must be capable of flowing 48 litres/ minute per sprinkler head at 100 kPa for the hydraulically most disadvantaged group of six sprinklers, for a minimum duration of 30 minutes. Given the different geographical locations of cities around Australia and variations in height above sea level, there are understandable variations in the supply pressures available in town main water supplies available to fire sprinkler systems. For the purpose of this study, we will assume a mean average town mains’ pressure of 500 kPa is be available. Given that we are looking at a study case building of 60 stories and each storey has an average height of 3.7 m (the floor-to-floor height of office buildings varies from 3.6 m to 4 m, however it is typically around 3.7 m), with an effective building height of approximately 222 m. When considering that gravitation/ elevation head loss is 9.8 kPa/m and the operating pressure to operate the 6 most hydraulically disadvantaged sprinkler is 200 kPa (+ friction losses), town mains pressure of 500 kPa can only supply water up to the eighth floor of the building. Therefore, town mains pressure is required to be boosted by a pump, to supply water to the sprinkler system for storeys above these lowest eight storeys.

The pumps are operated from separate pressure switches. These pumps are either electric or diesel operated. The levels of charge in the batteries or/and the continuity of the electricity supply are monitored, and battery/power failure is indicated by a local alarm and at the fire indicator panel (FIP).
AS 2118.1-1999 [8] requires that in the case of a multi-storey building in excess of 75 m (approximately 21 storeys), the sprinkler system needs to be divided into stages so that the pressure on any sprinkler does not exceed 1 MPa (1000 kPa). Considering that gravitation/ elevation head loss is 9.8 kPa/m and the operating pressure at the highest level (the most hydraulically disadvantaged sprinkler) is 200 kPa, then it is likely that the operating pressure at the lowest level is 200+ (75 x 9.8)+ losses ≈ 1000 kPa. This requires stages of ≤ ~20 storeys.

[*] This was reported as nearly 91.5% by both Kim [4] from US statistics of high-rise building fires in 1988 and Rohr and Hall [5] from US statistics of store and office fires in 1999-2002.

As discussed earlier, water can be supplied from the town main without a pump up to the lowest eight storeys. Therefore, the lowest stage usually consists of only eight storeys (see designs given in ref. 9) for high-rise buildings. The rest of the floors can be supplied with water in three ways:

- Upfeed system- by pump pressure only,
- Downfeed system- by gravity,
- A combination of the two.

For a 50 to 70 storey building, the system can be divided into the following stages in different ways as shown in Table 1:

TABLE 1. Staging options for a 50 to 70 storeyed building

Stage Name	*50 storey*	*60 storey*		*70 storey*
		Option I	*Option II*	
Low Stage	up to 8 storeys	up to 21 storeys	up to 8 storeys	up to 8 storeys
Mid Stage-I	9 to 29 storeys	22 to 42 storeys	9 to 29 storeys	9 to 29 storeys
Mid Stage -II	-	-	30 to 50 storeys	30 to 50 storeys
High Stage	30 to 50 storeys	42 to 60 storeys	51 to 60 storeys	51 to 70 storeys

For the purpose of this paper, Option I for a 60 storey building is considered in detail. Given the height of this building, there may be a need to have pump rooms for stage to stage pumping (plant rooms) or high pressure supply multi-stage pump along with high pressure riser.

Fig. 1 shows legends of symbols for various components of a sprinkler system.

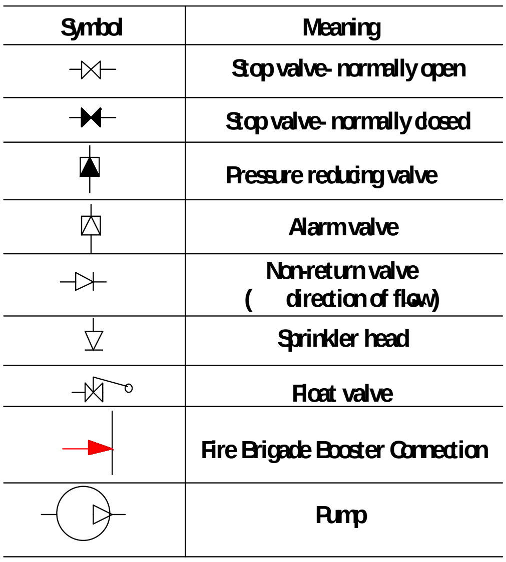

FIGURE 1. Legend of symbols

Water Supply for Upfeed System

AS 2941-2002 [10] allows the use of both single-stage or multi-stage pumps. In either case, one electrical and one diesel pump should be used. Single-stage pumps deliver water at a single pressure only, multi-stage pumps deliver water at different pressures suitable for different stages of a sprinkler system. In surveyed buildings, the use of single-stage pumps has not been observed for an upfeed system, rather multi-stage pumps are used. In the latter system, two multi-stage pumps can supply water to the whole building. Risers are connected to various stages of the pumps supply water to the different building stages with different pressures (see Fig. 2). Extra care needs to be used when designing this type of system to ensure that enough elevation head and friction loss is allowed for the correctly pressure rated pipework valves and fittings, to ensure that there is no failure. Water is either directly drawn from the town main or reservoirs/ tanks located in the basement. In these tanks, water is stored from town mains.

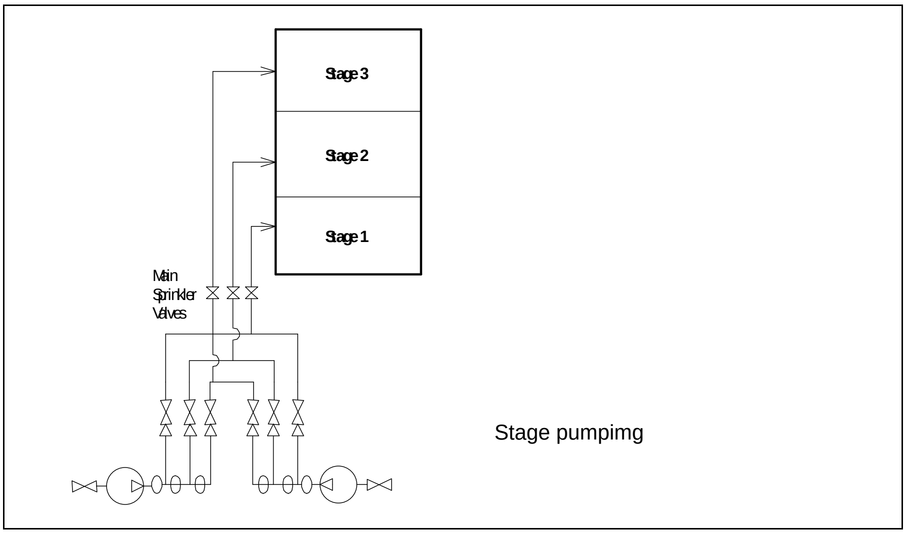

FIGURE 2. Water supply arrangement for upfeed system with multi-stage pumps

Water Supply for Downfeed System

A set of *very high pressure single-stage* pumps are usually used for a downfeed system covering the entire building. In this case *single-stage* pumps supply water directly to two gravity tanks at the top of the building. However as discussed previously, to supply water to a floor 20 storeys below the gravity tank, water pressure needs to be reduced. In a building with a multiple stage (each stage contains ~20 storeys) sprinkler system, a plant room is built above the floor at the end of each stage. In this floor, a riser from the upper stage feeds the riser of the lower stage with the help of one of the following options:

(a) a pair of pressure reducing valves to reduce water pressure for the lower stage
(b) a pair of cell tanks storing required amount of water, from which water is supplied for the lower stage

For both upfeed and downfeed systems, water is distributed to the risers supplying water to the respective sprinkler zones within each stage in the plant rooms.

Overall System Required by AS 2118

Tappings are, taken from each water main like tridents, used to transfer water for normal supply, sprinklers and fire hoses. For sprinklers, water is drawn and either supplied directly to the pump or stored in basement reservoirs/tanks and then is pumped to the riser. Water flows through non-return valves, pump isolation valves, the main sprinkler valve and then alarm valves to the riser. While water flows through the alarm valve, an alarm sounds to the fire brigade and to the building. A pump bypass system is usually provided to provide water under mains pressure to the lowest zone in the building, as a back-up supply. This system supplies water to only a few storeys (usually a maximum of eight).

Two different systems are shown in Fig. 3. A summary is given below:

TABLE 2. Sprinkler water supply systems

Figure No	*Type of System*	*Type of pump used*	*Remarks*
Figure 3(left)	downfeed	very high pressure single stage	just code compliant and usual practice
Figure 3(right)	upfeed	multistage	

In Fig. 3 (left) a set of *very high pressure single stage* pumps directly supplies water to the gravity tank placed at the top of the building. The gravity tank must be placed sufficiently above the roof to provide the required pressure for the sprinkler heads located in the top floor. Alternatively, a small low pressure pump is used to achieve protection for the first few floors at the top of the building.

In each plant room a set of pressure reducing valves are installed to regulate the water pressure appropriately for the sprinklers and piping system in the stage below.

A set of pressure reducing valves is installed to regulate the water pressure appropriately for the sprinklers and piping system in the stage below. Alternatively a pair of cell tanks, storing required amount of water, from which water is supplied for the lower stage, are installed.

In Fig. 3 (right), a set of *multi-stage* pumps supplies water to different stages over the height of the building. These pumps can provide water at suitable pressures in different heights of the building. At plant rooms, *typical risers* emanate from the main riser supply water to separate zones of each stage. The number of *typical risers* per stage is considered to be three in this study.

FAULT TREE CONSTRUCTION

A number of fault trees has been constructed based the systems shown in Fig. 3. The top event is selected as sprinkler does not deliver at the most disadvantageous locations of the building. One of the fault trees for a downfeed system where sprinkler does not deliver water at a location at stage 2 is presented in Appendix A. The fault tree is expanded up to only six levels in Appendix A. Further expansion can be viewed in ref. 12.

QUANTITATIVE EVALUATION/ SURVEY

To calculate the top event frequency or probability, each basic event or undeveloped event need to be assigned a probability or frequency. Frequency represents the number of events expected per unit time period (e.g., fires per year). On the other hand, probabilities are dimensionless and can be used to describe the likelihood of occurrence of an event ranging from 0 to 1. 0 means the event will never occur and 1 means the event is certain to occur. Sum of all possible states is equal to 1. Using an example of drawing a card from a pack of 52 well-shuffled playing cards, the probability of drawing a spade (i.e., event E = 'a spade is drawn') is given by:

$$P(E) = \frac{\text{number of outcomes corresponding to event E}}{\text{total number of outcomes}} = \frac{13}{52} = 0.25 \qquad [1]$$

The probability of drawing any card (spade, hearts, diamond or clubs) i.e. sum of all possible state is 1. This example is applicable when all outcomes are equally likely.

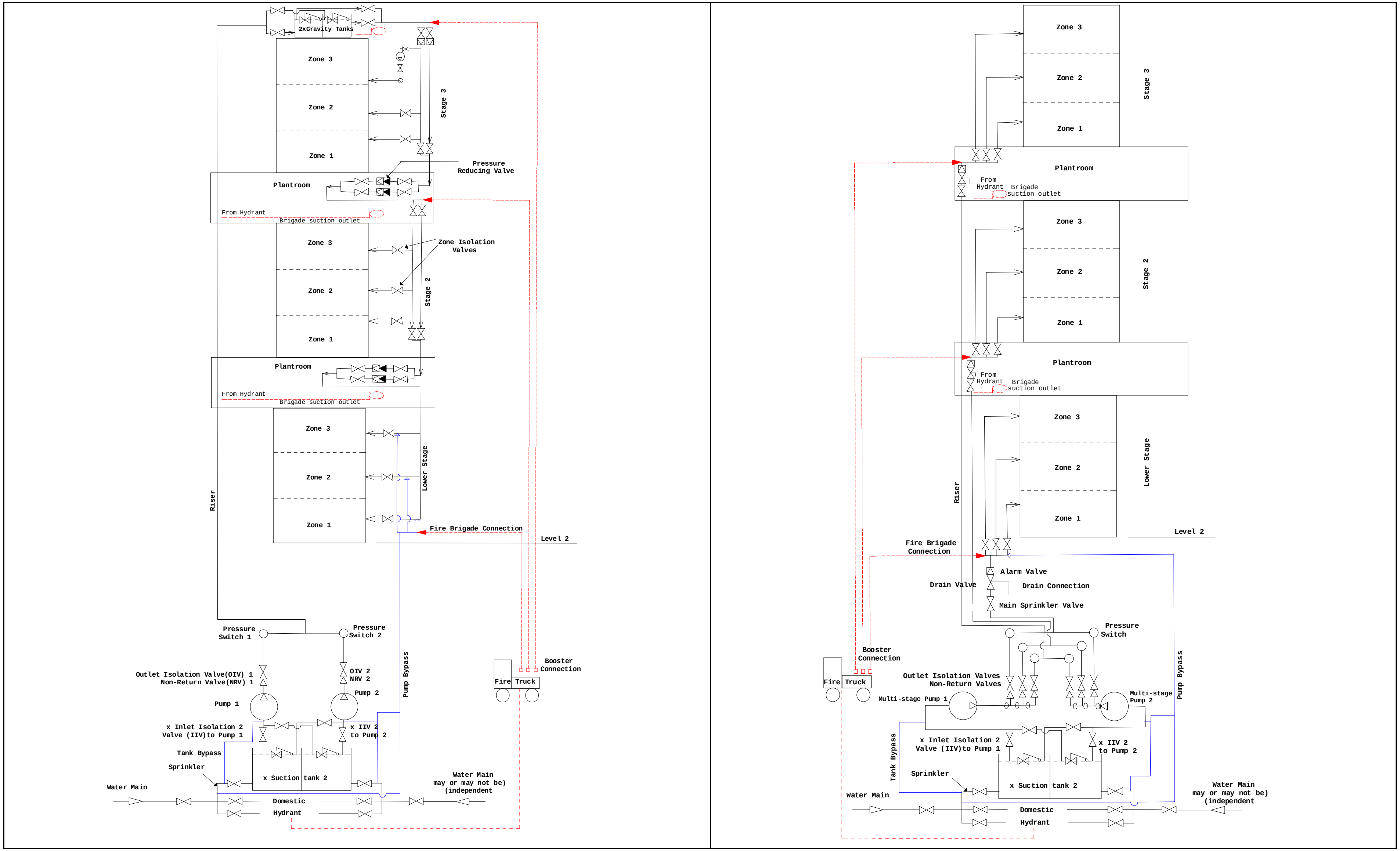

FIGURE 3. Details of water supply and sprinkler system for 60 storey building: (Left) Downfeed and (Right) Upfeed

To facilitate the calculation of the top event frequency or probability, the frequency of the relevant components failure (failure rate per demand or per unit time) of the system is required. If any component's failure frequency (λ) and the interval between two successive maintenance visits (t) are known, the probability of the failure or failure rate per demand (P) can be found by:

$$P = 1 - e^{-\lambda t} \qquad [2]$$

With the interval between two successive maintenance visits time taken by the owner to repair or replace faulty components should also be added.

The information on failure rate can be collected in the following two ways:

a. Evaluating the published surveys and reports
b. Conducting a survey on a number high-rise office buildings in Australia. One of the major focus will be to find out how much time is taken by the owner to repair and replace faulty components

If failure frequency (λ) is found in the above publications it will be converted to failure rate per demand (P) by using maintenance frequency given in AS1851-2005 [11] plus time taken by the owner to repair or replace faulty components as t.

Review of the Existing Data (Australian and Overseas)

A collection of failure data from 17 sources is tabulated in Table 3. Due to the space constraint all references are not listed in this paper. However complete references can be found in ref. 12. The majority of the tabulated data came from three sources: VTT [13], 140 William St [14] and Rasmussen report [15]. Based on following arguments the literature data can be used for estimating the reliability of sprinkler system in a high-rise office building:

- VTT data [13] are mainly based on a survey on the sprinkler systems of 102 sample buildings (sprinklered and not related to nuclear industries) which represents some 5% of the number of sprinklered buildings in Finland. Of these, nearly 20% represents office buildings. However some data is based on the survey from nuclear power plant (NPP)s, but it is stated in the report that sprinkler technology in NPPs is almost identical with the technique used in other industrial installation and only maintenance actions and periodic testing are better controlled in NPP than elsewhere. It is expected that Australia, Finland and other west European countries use main sprinkler system components from the same manufacturers (mainly US based).

- 140 William St data [14] are mainly based on interviews with sprinkler maintenance personnel and inspection of maintenance log book in Melbourne, Australia. Some of the information was also supplied by Fire Brigade.

- The data from Rasmussen report [15] are not specific to sprinkler system. This data were obtained from both nuclear and non-nuclear sources in US, but were collected for use in nuclear hazard asssesment, in particular on the critical loss of coolant accident. This study was a major exercise involving some 70 man years of work. The failure data provided in ref. 15 for most of the components are similar to the other available sprinkler data sources i.e. have the same order of magnitude in figures.

TABLE 3. Failure rate of system components from references 17-33 of ref. 12, Gray highlight is taken as the literature best figure for FTA

	Maint. freq. (yr)	Failure rate/ per year	Failure rate/ per demand (converted from Col 3)	Failure rate/ per demand
Alarm valve	.0833	0.4×10^{-4} [17] $6.5, 12, 20 \times 10^{-4}$ [19]	$.0333 \times 10^{-4}$ [17] $0.542, 1, 1.67 \times 10^{-4}$ [19]	1×10^{-4} [23]
Main stop valve	.0833	0.2×10^{-3} [17]	$.0167 \times 10^{-3}$ [17]	$5.48, 54.8, 548 \times 10^{-3}$ [19] 0.1×10^{-3} [23]
Subsidiary stop valve due to tenancy changes	.0833			2.47×10^{-2} [18],(3)
Ordinary Stop valve	.0833	0.2×10^{-3} [17]	$.0167 \times 10^{-3}$ [17]	$5.48, 54.8, 548 \times 10^{-3}$ [19], 0.1×10^{-3} [23]
Non-return valve	.0833	1.0×10^{-2} [17]	8.33×10^{-4} [17]	$0.3, 1.0, 3.0 \times 10^{-4}$ [19] 0.1×10^{-4} [23]
Alarm motor		1.6×10^{-2} [17]	0.133×10^{-2} [17]	$2.681, 3.62, 4.81 \times 10^{-2}$ [19]
Sprinkler head				320×10^{-4} [17] 0.01×10^{-4} [18], [19]
Town main		$2.6, 10, 25 \times 10^{-4}$ [19]		1.5×10^{-4} [18]
Gravity tank	12			2.28×10^{-4} [18] $+ 3.64 \times 10^{-4}$ [28]
Storage tank	12	$0, 0, 0.65 \times 10^{-4}$ [19]	$0, 0, 7.8 \times 10^{-4}$ [19]	2.28×10^{-4} [18] $+ 3.64 \times 10^{-4}$[28]
Water supply line (per m)	.0833	$2.4, 3.3, 4.3 \times 10^{-6}$ /m[19]	$2.0, 2.75, 3.58 \times 10^{-7}$ /m[19]	2.6×10^{-6} [29]
Back-up batteries for the diesel pump	.0833	2.63×10^{-2}, [23]	2.19×10^{-4},[23], (12)	8.0×10^{-4} [18]
Back-up batteries for FIP panel	.0833	2.63×10^{-2}, [23]	0.219×10^{-3},[23], (12)	1×10^{-3} [18]
Mains power in building				5.0×10^{-5} [18]
Pressure switch (assumed same for the diesel and electric pump)				10×10^{-4} [18] 1.0×10^{-4} [23]
Diesel pump	.0833	$8.7, 15, 23 \times 10^{-3}$ [19] $0.0, 14.9, 58 \times 10^{-3}$ [33], 20×10^{-3} [18]	$0.73, 1.25, 1.91 \times 10^{-3}$ [19] $0.0, 1.24, 4.82 \times 10^{-3}$ [33] 1.67×10^{-3} [18]	3×10^{-3} [23]
Electric pump	.0833	$2.5, 6.2, 13 \times 10^{-3}$ [19], 20×10^{-3} [18]	$0.21, 0.52, 1.08 \times 10^{-3}$ [19], 1.67×10^{-3} [18]	0.3×10^{-3} [18]
Direct brigade alarm faulty				1×10^{-4} [18]
Pressure reducing valve	1			0.05×10^{-3} [23] 10×10^{-3} [25],[27] 4.37×10^{-3} [26]
FIP	.0833	8.76×10^{-3} [23],(20)	7.3×10^{-4} [23]	9.7×10^{-5} [34]
Monitor alarm/sensor	.0833	8.76×10^{-3} [23],(21) $6.4, 29, 64 \times 10^{-3}$ [33] $1.2, 25, 120 \times 10^{-3}$ [33]	7.3×10^{-4} [23] $0.53, 2.41, 5.3 \times 10^{-3}$ [33], $0.1, 2.08, 9.95 \times 10^{-3}$ [33]	1.82×10^{-2} [30]
Fail to observe monitor alarm activation				3.0×10^{-2} [24]
Wiring burn out	.0833	2.63×10^{-3} [23]	2.19×10^{-4} [23]	
Mechanical failure of diesel pump	.0833	2.68×10^{-1} [23]	2.21×10^{-2} [23]	
Underground pipe from town mains to tank corroded				1.0×10^{-4} [32]

Sprinkler Downtime due to Work during Tenancy Change

In most buildings the only means of intercepting the water flow to a floor during a tenancy change is to turn off the sprinkler valve on the riser. Fig. 3 shows that eight floors are connected by one subsidiary valve. Therefore, all connected floors are out of sprinkler water supply for number of days. The probability of the sprinkler valve turned off, P(E), can be calculated as:

$$P(E) = \frac{\text{no of tenancy changes in a yr} \times \text{no of days required in each change} \times \text{no of fls connected to a valve}}{\text{total no of fls in the building} \times \text{no of days in a yr}} \quad [3]$$

The fault tree analysis given in 140 William St [14], showed that in a building constructed code-compliant P(E) could be 0.0297 for a particular building and similarly applying to Figs. 3 and 4, we get a value of 0.0247 (see Table 3). In ref. 14, it was found that sprinkler valve shut off during tenancy changes was the main factor that may lead to a sprinkler system failure.

Collection of New Data

A survey is currently being conducted on a number of Australian High-rise office buildings. In order to carry out this survey, huge efforts were required to obtain the contact details of the building managers/ owners. Once the building managers/ owners were contacted, the purpose of the study was explained and a questionnaire was sent out, in order for them to fully understand what was needed to obtain from them. Although the response was not quite encouraging, it was possible to get a response from 13 different buildings, with a few more lined up in the coming months. However, of these 13 buildings, the results of nine buildings have been found successfully relevant to the analysis. The identification details of these buildings were kept confidential and only the agglomerated data were used for the research.

During the visit to the different buildings, two of the authors followed a standard questionnaire and consulted the following documents:

- Schematic diagram of the sprinkler system
- Records of sprinkler component repair/replacement works
- Records of informing fire brigade and insurer about sprinkler isolation of certain floors (system impairment) due to tenancy change etc.
- Records of periodic testing of sprinkler components

Unfortunately, not all records of the above documents for the entire life of the building were kept, due to change in management or the records were archived, therefore some buildings only had records for the last two to five years.

Due to the probability of subsidiary isolation valves remains shut was found to be the primary reason to cause the system failure, emphasis was given to following questions during the survey:

- How many floors are attached to a subsidiary isolation valve?
- No of hours a floor is isolated in a year? Is it done during the day? Or night?
- No of tenancy change in a year (averaged over the building life)?

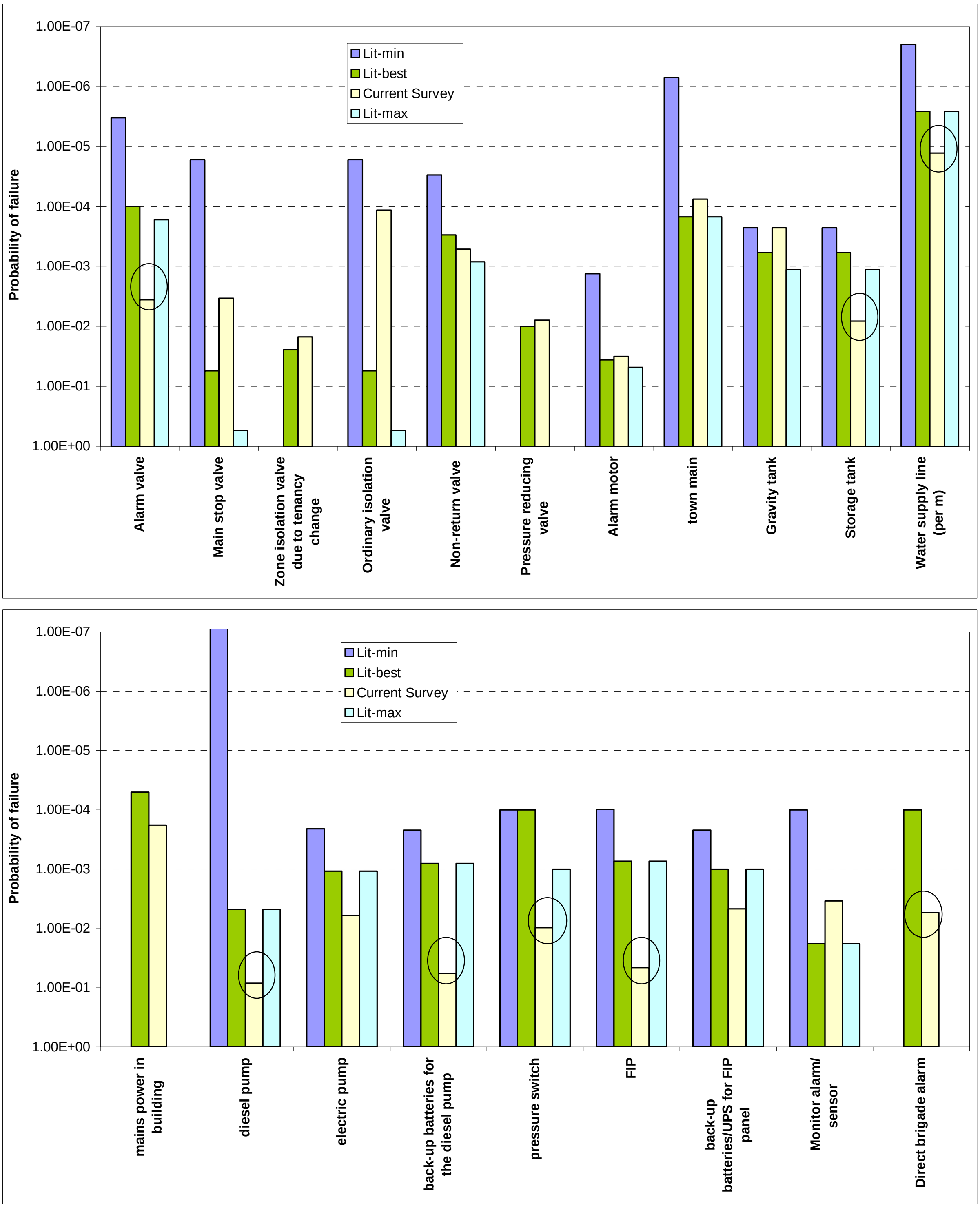

FIGURE 4. Comparison of results between literature and current data

The number of each components were counted from the schematic diagram in order to find its failure rate per year. During the survey, building facilities/ fire service mangers were also asked the time taken to repair or replace faulty components, to specify the correct interval between two successive maintenance visits. This is essential, as it enables us to convert failure rate into probability using equation [1].

Unfortunately, “fail to observe monitor alarm activation and take action by operator”, “wiring burn out” and “underground pipe from town mains to tank corroded” could not be determined in the survey; therefore the data from Table 3 needs to be used. It was also not possible to find the reliability of sprinkler heads. Of 3 figures mentioned in Table 3 the value of 1E-06 is selected as [13] opined (in pg 34) that there must happen a strong selection of faulty components for tests reported in reference 17 of ref. 12. Therefore that figure is not considered at all.

RESULTS AND DISCUSSION

It has been found from the survey that during the tenancy changes, sprinkler valves are only shut during the daytime. In some buildings, it was restricted to only shut sprinkler valves during weekends. The buildings have the policies of restriction on sprinkler isolation time, which varies from 8 to 10 hours a day. During night, all pipes are pressurised. With this policy, the risk of sprinkler impairment is reduced two to three times. Therefore, equation [3] is changed to:

$$P(E) = \frac{\text{no of changes per yr} \times \text{no of days per change} \times \text{no of hrs per day} \times \text{no of fls connected to a valve}}{\text{total no of fls in the building} \times \text{no of days per yr} \times \text{no of hrs per day}} \quad [4]$$

It has also been found that the building facility/ fire service mangers are aware of the dangers during tenancy change period, which is further exacerbated by the fact that at the same time hot-working is also carried out. In many buildings for such periods, physical patrolling is arranged. Applying equation [4] to surveyed building data, *mean* P(E) is found to be 0.0151 which is significantly lower than 0.0247 calculated for Fig. 3 based on ref. 14.

The results of *mean* failure probability of each component are plotted in Fig. 4 along side data of Table 3. From the literature (Table 3), minimum, maximum and most relevant (literature best) figures are presented. The vertical axis is in logarithmic scale and the numbers are shown in inverse order i.e. the longer the column the lower its failure probability. Out of 20 components, 12 components data are found to be within the same order of magnitude of the data found in the literature (Table 3). The remaining eight components’ (indicated by an oval in Fig. 4) failure probabilities are found to be much higher than the literature data.

From the survey the *mean* failure probabilities of building power generator and back-up batteries for brigade alarm are found as 1.15E-01 and 8.15E-03 respectively.

From FTA the reliability of sprinkler system for different systems are shown in Table 4:

TABLE 4. Reliability of sprinkler system

Figure No	*Type of System*	*Based on literature data*	*Based on current survey*
Figure 3(left)	downfeed	97.17%	97.95%
Figure 3(right)	upfeed with no basement tank	96.90%*	97.98%

It can be observed that based on both literature and current survey data, sprinkler system reliability in Australian high-rise building lies in between commonly considered values of 95% (non-flashover fire) and 99% (flashover fire) [16]. The provision of pressurising sprinkler system during night time at the duration of tenancy changes has significantly improved the reliability. However, the reliability figure from FTA could not be compared with the one from fire statistics as sufficient Australian data is not available.

* This was estimated as 96.85% by ref. 13.

CONCLUSIONS

The use of a physical survey is an effective means of gathering detailed information on factors affecting the reliability of sprinkler system. Although it was challenging to involve the building owners in the study, it was possible to come up with some data by consulting relevant documents. Whether there were records kept of the entire life of the building or only up to two years, these documents allowed to calculate the failure probability of various components of sprinkler system. In the process, time taken to repair or replace faulty components has been incorporated.

The results show that out of 20 components, 12 components of the data are found to be within the same order of magnitude of the data found in the literature. The remaining eight components' failure probabilities are found to be much higher than the literature data. However, the sprinkler zone shut off during tenancy changes probability is found to be significantly lower than the figure initially estimated based on ref. 14. This outweighs higher failure probabilities of eight components and as a result the sprinkler system in Australian high-rise buildings is likely to be more reliable than that based on literature data as well as commonly considered figure.

In spite of the improvement in reliability with respect to the sprinkler zone shut off during tenancy changes, it remains the main cause leading to a sprinkler system failure. In regards to this, building facilities/ fire services managers take extra precaution of the dangers involved during tenancy changes, and often adopt a solution of physically patrolling the area.

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APPENDIX A: FAULT TREE OF A DOWNFEED SPRINKLER SYSTEM