THE RELIABILITY OF PUMP-SETS IN HIGH-RISE BUILDINGS

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ABSTRACT

A reliability study on up feed and down feed pump-sets in high-rise buildings in Hong Kong was carried out. Event tree analysis [1] was used to analyze the reliability of the pump-sets configuration. The mean value of failure rate [2] of the pumps was concluded from two data files [3] with about 15000 records. Different values of the mean fractional dead time [4] from different proof test interval [5], which representing the failure probability of the pump-sets configuration were calculated and compared. Shortening the proof test interval can just raise a little reliability of the pump-sets, but the increase in cost would be quite large. The reason for using two pumps (one duty and one standby) instead of using three or four pumps was analyzed.

1. INTRODUCTION

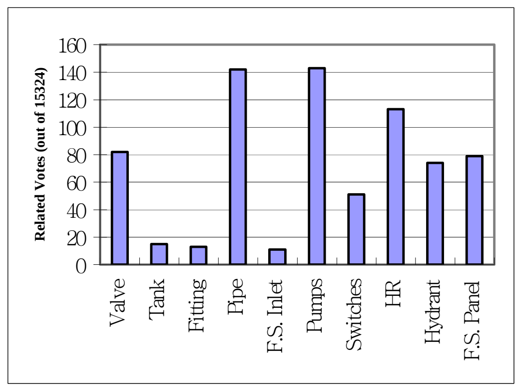
Reliability is a kind of probability [6]. The probability of an event is the proportion of times that observed from the event in a large number of trials [7], or the expected proportion that would appear. Probability can be indicated in fraction, decimal number and percentage.

Reliability has two connotations [8]. The first one is probabilistic in nature and the second one is deterministic. The definition of reliability is the ability of an event to operate under designated operating conditions for a designated period of time. In the probabilistic approach, reliability of a system is the probability to operate it successfully for a prescribed time. In actual case, repair of components after system failure can also be added to the analysis or calculation. Otherwise, the system is either in operation or it fails [9]. In the deterministic approach, it includes deterministic analysis and review of the failure report, understanding the physics of failure.

"Pump-sets" is a network connecting the pumps inside the building, such as Sprinkler pumps, Fixed fire pumps (F), Intermediate Booster pumps (I) and Transfer pumps (T), each including a Duty (D) and a Standby (S) pump. "High-rise building" means any building of which the floor of the uppermost storey exceeds 30 m above the point of staircase discharge at ground floor level [10].

Since 1997, a new airport was built at Chek Lap Kok which is far away from the urban districts, skyscrapers are possible to appear in the urban part of Hong Kong. A successful operation of pumps (especially the sprinkler pump) can help controlling the fire size before and after the arrival of firemen. So the reliability of the pumps should be as high as possible.

Graph A was plotted using a data source obtained from Electrical and Mechanical Services Department (EMSD) of Hong Kong through an engineer.



Graph A: Distribution of fire services installations among the sources

The data source included the replacement, repairing and maintenance records of the Fire Services Installations. In Graph A, it can be found that pipe works and pumps had a higher portion in the records. It is necessary to take a look at their reliability. But only the reliability of pump-sets would be concerned in this report.

Reliability of a system can be improved by checking more frequently, but the higher the frequency, the higher the cost. Life safety is very important, but when overprotected, large amount of money would be wasted. In order to find a balance between these two issues, some calculations are required.

2. METHODOLOGY

2.1 Assumption

In this report, probability of different situations would be calculated. In order to limit the number of situations being concerned, to simplify the whole system to make it easier to understand, some assumptions were made during the consideration about the reliability of different pump-sets.

- Only Fixed fire pumps (F), Intermediate Booster pumps (I) and Transfer pumps (T), each including a Duty (D) and a Standby (B) pump, inside the building were considered.
- All the pumps (F, I, T, D, B) were identical and having the same reliability.
- The failure rate in any period was kept constant.
- The operating conditions of the pumps were kept constant throughout the whole process during a fire.
- There were only two outcome events for each pump after receiving starting signal (succeed or failure).
- Only the configurations of up feed and down feed water distribution system [11] were considered.

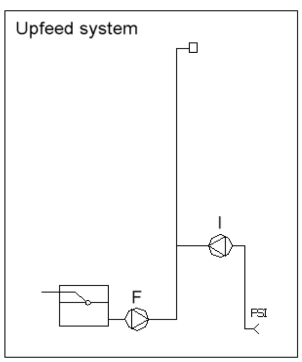


Fig. 1: Schematic diagram of an up feed

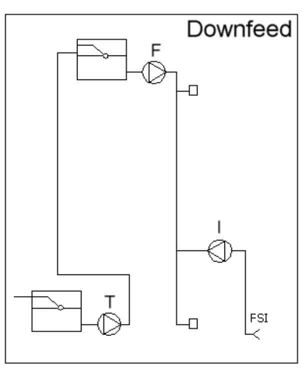


Fig. 2: Schematic diagram of a down feed pump system

2.2 Fractional Dead Time

In order to determine the reliability of a pump-set, the reliability of a single pump should first be found. The mean fractional dead time (FDT) was the average failure probability of the system over a given period of time. The FDT based on an exponential distribution of failure rate was given by:

$$\mathrm{FDT} \cong \frac{1}{\tau}\int_0^{\tau}\left(1-e^{-\lambda \cdot t}\right)\mathrm{dt} \qquad (1)$$

For $\lambda t << 1.0$, equation (1) becomes:

$$\mathrm{FDT} \cong \frac{1}{\tau}\int_0^{\tau}\left(1-[1-\lambda t+\frac{(\lambda t)^2}{2!}+...]\right)\mathrm{dt} = \frac{\lambda\tau}{2} \qquad (2)$$

where λ was the failure rate (per hrs) for a system component and τ was the proof test interval (hrs).

The need of fire pumps was equally probable at any instant over the proof test interval as the occurrence of most fires were unpredictable or accidental. The mean value of λ can be concluded from the data source. In equation (2), if λ was kept constant, the FDT of a pump could be reduced by lowing the value of τ. The proof test interval used in fire protection system in Hong Kong is one year (8760 hrs) [12].

Reliability of a system is the probability to operate it successfully for a prescribed time.

$$\text{Reliability} = 1 - \text{FDT} \qquad (3)$$

Combining equations (2) and (3):

$$\text{Reliability} = 1 - \frac{\lambda\tau}{2} \qquad (4)$$

Different values of τ would be used to calculate the reliabilities of the two systems. A graph would be plotted on reliability against τ to observe the differences.

2.3 Reliability of Series and Parallel Systems

The method to calculate the reliability of a single pump is shown below [13]:

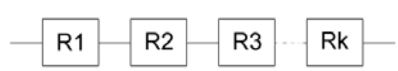


Fig. 3: Schematic diagram of a series pattern system

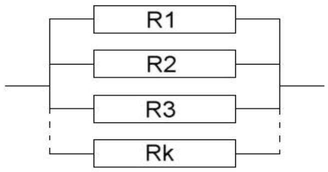


Fig. 4: Schematic diagram of a parallel pattern system

The reliability of a series system can be calculated by:

$$R_p = R_1 \times R_2 \times R_3 \times \ldots \times R_k \qquad (5)$$

The reliability of a parallel system can be calculated by:

$$R_p = 1 - (1 - R_1)(1 - R_2)(1 - R_3)\ldots(1 - R_k) \qquad (6)$$

where R_p is the parallel system reliability, R_s is the parallel system reliability, R_i is the unit **i** reliability, for **i** = 1, 2, 3, …, k.

2.4 Event Tree Analysis

Using Event Tree Analysis (ETA) can help people understand the structure of the system easier as it is the most widely used risk assessment technique. There is a difference between ETA with other “Tree Analysis”. ETA also considers the sequence of events according to their occurring time. As it is assumed that there are only two outcome events for each pump after receiving starting signal (succeed or failure), ETA is suitable to be used to analyze the reliability of pump-sets. Each path has its own occurence probability.

Fig. 5 shows that the upward pathway represents a successful operation while the downward pathway represents a failed operation. Figs. 6 and 7 are the ETA diagram of up feed (Fig. 1) and down feed system (Fig. 2) respectively. Each branch shows one combination of the sequence of pumps operation. The number of pumps used in the down feed system are more than in the up feed system. The reliability of each branch could be obtained by multiplying all the related probabilities at its T-off points. Then, the reliabilities of the systems could be obtained by summing up the probabilities of branches that could be actuated successfully.

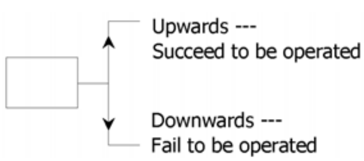
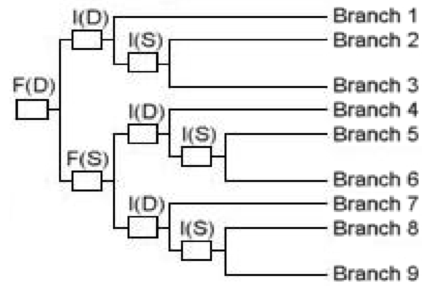


Fig. 5



F = Fixed fire pumps I = Intermediate booster pumps
T = Transfer pumps
(D) = Duty pump (S) = Standby pump

Fig. 6: The ETA diagram for an up feed system

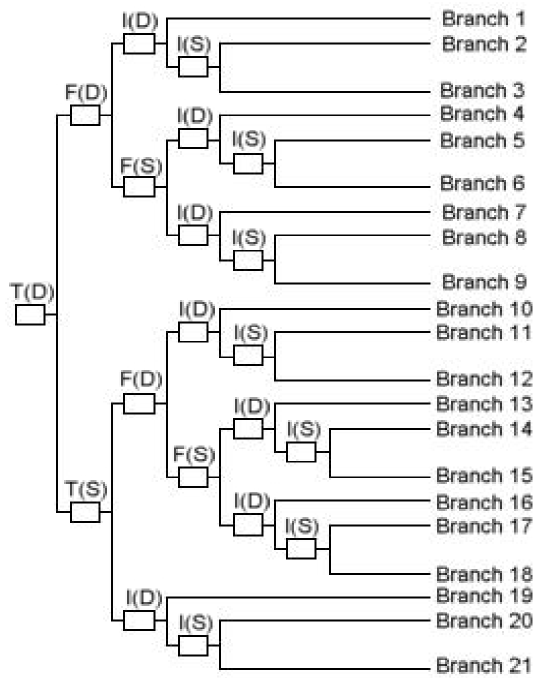


Fig. 7: ETA diagram for a down feed system

2.5 Comparison

The proof test interval (τ) for fire pumps system in Hong Kong is one year (8760 hrs). The main objective of this report is to compare the system reliability calculated using proof test intervals equal to one year (8760 hrs) to others using different proof test intervals to find out their relative differences. Using different values or τ would vary the maintenance cost of the systems. The differences in maintenance cost would be calculated and compared to the relative differences in system reliabilities to find out whether it would be worth to change the τ to raise the reliabilities or to save money.

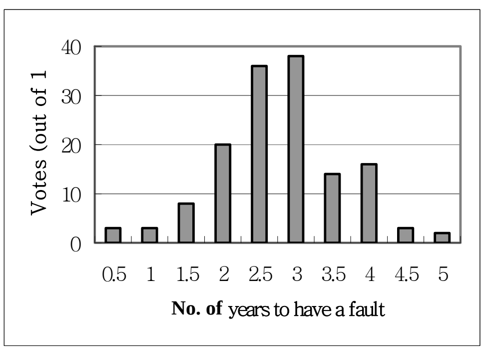
Each pump set in Hong Kong consists of two main pumps, duty and standby, and forms a parallel network. From equation (6), the more the pumps connected in a parallel system, the higher the reliability. By comparing the reliabilities of parallel networks with two, three and four pumps, the reason why only two pumps are in a pump-set can be found.

3. DATA AND ANALYSIS

Failure rate (λ) is the main parameter in calculating the reliability. In this report, the mean value of λ was concluded and extracted from two data files from EMSD. There were a total of 15000 records in these files. They were the maintenance records of Fire Services Installations among the government buildings in Kowloon. The date of the records started in 1998 and ended at the beginning of 2004. The time period was about five years. Within these five years, out of 15000 records, 143 records related to replacement or repairing of pumps were extracted out. It was assumed that such replacement or repairing works were done after the faults of the pumps during the maintenance stage.

3.1 Reliability of a Single Pump

Graph B was plotted using the records extracted from the data files (from EMSD). This graph shows the distribution of the time period that a pump required repairing or replacement. The time periods were classified using half-year as the time interval.



Graph B: Distribution of failure rate (λ)

An interesting figure was obtained. A distribution with the highest voting in the middle and less at the two ends was shown in Graph B. It looked like a normal distribution. The columns of 2.5 and 3 years had the highest votes. There was a fault of pumps mostly about 2.5 to 3 years after installation.

2.75 years was chosen as the mean value of the failure rate (λ) of a pump in the following calculations. So, $\lambda = 0.364\ yr^{-1} = 4.19 \times 10^{-5}\ hr^{-1}$. Failure rate is an important variable in calculating the reliability of pumps. From equation (4), the longer the time period to have a fault, the lower the value of λ and a higher value of reliability would be obtained.

Four values of proof test interval (τ) were used to calculate the reliability of a signal pump. From Table 1, take τ = 8760 hrs as the reference point, the reliability of a pump is inversely proportional to the value τ. The reliability would be increased by shortening τ and decreased by extending τ. It was not difficult to understand that more frequent inspections could raise the reliability of a pump. The differences in reliability shown was compared to τ = 8760 hrs. When τ was shortened to 0.5 year, the reliability would be raised by 11.4 %. When τ was enlarged to 1.5 and 2 years, the reliability would be decreased by 11.3% and 18.9% respectively.

Table 1: Reliabilities of a single pump

	τ = 4380 hrs (0.5 year)	τ= 8760 hrs (1 year)	τ = 13140 hrs (1.5 years)	τ = 17520 hrs (2 years)
FDT	0.092	0.183	0.275	0.367
Reliability	0.91	0.817	0.725	0.633
Difference (comparing toτ= 8760)	+ 11.4 %	0	(- 11.3 %)	(- 18.9 %)

3.2 Reliability of Upfeed and Downfeed Pumping System

As the entire fire pumps were assumed to be identical, they would have the same reliability. By using ETA, the reliability of each system could be determined.

Table 2 was concluded from the ETA diagram for the up feed (Fig. 6) and down feed (Fig. 7) systems. The flows of the blocks (T, F, I, D, S) in the figures are following the sequence of pump operations. The concept used in analyzing the distributions of the tree in these two figures is just the same.

Table 2: Reliability of systems analyzed by one ETA diagram

		τ = 4380 (0.5 year)	τ = 8760 (1 year)	τ = 13140 (1.5 years)	τ = 17520 (2 years)
Upfeed system	System reliability	0.992	0.967	0.924	0.865
	Percentage changes	+ 2.6 %	0	(- 4.4 %)	(- 10.5 %)
Downfeed system	System reliability	0.992	0.967	0.924	0.865
	Percentage changes	+ 2.6 %	0	(- 4.4 %)	(- 10.5 %)

In Fig. 6, the duty pump (D) in fixed fire pump-set (F) was actuated after receiving a fire signal. If it failed to operate, the standby pump (S) would be actuated automatically within 15 s. After the arrival of firemen, the intermediate booster pumps (I) would be actuated manually and the fixed fire pump would be interlocked automatically. The sequence of actuations of the duty and standby of intermediate booster pump-set is just similar to that of fixed fire pumps. The reliability of a system could be obtained by summing up the probabilities of the branches that could be actuated successfully. The down feed system has one more pump-set transfer pump (T) in the configuration of the whole system. So, Fig. 7 is more complex, but the concept in constructing the tree is the same as in Fig. 6.

Although the construction and the number of branches of these two ETA diagrams are different, their reliabilities compared to different proof test intervals were found to be the same. The values of reliability would be increased by shortening τ and decreased by extending τ.

The ETA could only analyze the events correctly whose sequences are dependent to each other. The fixed fire pumps and intermediate booster pumps are independent to each other although they have a relationship in the operating sequence. If one of them is out of order, the other one could still be actuated and its reliability would not be affected. Although the sequence of pumps are shown in Fig. 6 and 7 clearly, they were combined by two independent network. And there was not a direct connection in water supply between them. So, the result could neither represent the reliability of the pump networks nor the reliability of water supply of the whole system. It just showed the reliabilities after the arrival of firemen. It was not suitable to analyze the whole system using only one ETA diagram and so, the results shown in Table 2 for the two systems are the same.

The fixed fire pump-set is dependent on the transfer pump-set and there is a direct water connection between them. A series network is formed between them automatically [14]. If the transfer pump-set fails, the water supply to fixed fire pump-set would be stopped. ETA is suitable for analyzing the relationship between these two events. Thus, a correct way to analyze the whole system should first divide it into two networks according to the relationship in water supply and also the partnership in operation. It was found that each of the up and down feed systems could be divided into two independent pump-set networks according to two time intervals, before the arrival and after the arrival of firemen during a fire. Each was then analyzed by one ETA diagram. Then, the reliability of the whole system could be determined using equation (5).

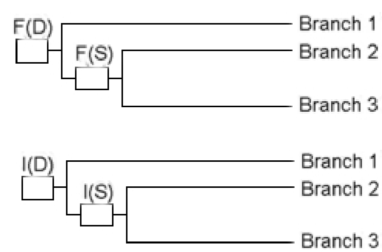


Fig. 8: The ETA diagram for network

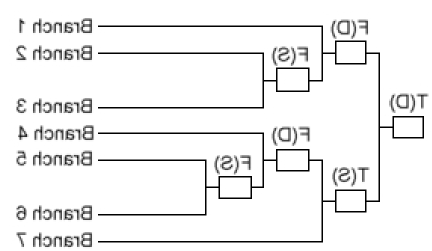


Fig. 9: The ETA diagrams for network for F or I only among T & F

Table 3: Reliability of the systems at two intervals

Period of time	Before arrival of firemen		After arrival of firemen		* Reliability
	Pump(s) actuated	Reliability	Pump(s) actuated	Reliability	
Upfeed	F	0.967	I	0.967	0.934
Downfeed	T + F (series network)	0.934	I	0.967	0.903

* Reliability of the system that the pumps could be actuated successfully at both intervals.

Table 4: Reliability of the systems analyzed by two ETA diagrams

		τ = 4380	τ = 8760	τ = 13140	τ = 17520
Up feed system	System reliability	0.984	0.934	0.855	0.749
	Percentage changes	+ 5.35 %	0	(- 8.46 %)	(- 19.8 %)
Down feed system	System reliability	0.976	0.903	0.790	0.648
	Percentage changes	+ 8.08 %	0	(- 12.5 %)	(- 28.2 %)

In Table 4, proof test interval of 8760 hrs (one year) was used as an example to show the reliability of each pump-set, their combinations at each interval and also the reliability of the whole system (also the reliability of water supply). Each pump-set was formed with a parallel network by one duty pump and one standby pump. The ETA diagrams of fixed fire pump and intermediate booster pump are showed in Fig. 9. At the periods before the arrival of firemen in the down feed system, the two parallel networks (T & P) were operated together and formed a series network. Its corresponding ETA diagram is shown in Fig. 8. The method used to analyze the ETA diagrams was the same as that for Figs. 6 and 7, which was mentioned before.

The reliabilities of these two systems are the same after the arrival of firemen as the same type of pumps (intermediate booster pump) were used. But their reliabilities are different before the arrival of firemen due to different configurations of pump connection. One more pump-set (transfer pumps) was used in the down feed system. For a series network, the more the components connected, the lower the reliability of the whole system. The reliabilities of the systems that the pumps could be actuated successfully at both intervals are listed in the last column in Table 4. The value of up feed system is higher than that of the down feed system. Such values could not represent the reliabilities of water supply of the systems. It is because such calculating concept was just joining two independent components together. The reliabilities of water supply at these two intervals are also different.

Table 4 shows the system reliability and also the percentage changes, calculated from two ETA diagrams for each system and following the division in Table 3. The reliabilities of the up feed system with respect to different values of proof test interval are all higher than those of the down feed system. The values of reliability in both systems increased when shortening τ and decreased when extending τ. But the percentage changes in reliability in the up feed system are more moderate when compared to that of the down feed system. The pump-set operating in the down feed system is more than that of the up feed system. And the pump-set was operated in a series network following the sequence. In equation (5), the more the components connected in a series network, the lower the overall reliability of the system. When there is a reduction in reliability of each component, the one with more components would have a higher overall reduction.

Table 5 shows the maintenance cost (MC) of each system within 50 years. This maintenance cost mainly covers the labor, repairing and replacement cost [15]. 50 years was chosen as the maintenance life, because mostly a building life was also assumed equal to 50 years. That means the availability of the pump system inside the building would also be at least 50 years. As mentioned before, down feed system has one more pump-set than the up feed system. The maintenance costs of down feed system are higher. The degree of percentage changes in the two systems is the same as there are the same effects from the proof test interval.

Table 5: Maintenance cost of the systems

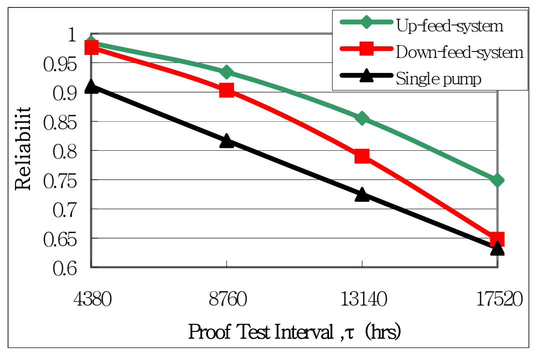
		τ = 4380	τ = 8760	τ = 13140	τ = 17520
Up feed system	Maintenance cost within 50 years ($)	206600	103300	68200	51650
	Percentage changes	+ 100 %	0	(- 34 %)	(- 50 %)
Down feed system	Maintenance cost within 50 years ($)	310000	155000	103000	77500
	Percentage changes	+ 100 %	0	(- 34 %)	(- 50 %)

Table 6: Reliability of parallel network

Proof test interval	Reliability of a single pump	Reliability for a parallel pump network		
		2 pumps	3 pumps	4 pumps
τ = 8760 hrs (1year)	0.817	0.967	0.994	0.999
Percentage changes	0	18.3%	18.3 + 3.4 = 21.7 %	21.7 + 0.6 = 22.3 %
Cost increased	0	100 %	200 %	300 %

3.3 Parallel Network

Table 6 shows the reliability of parallel networks with different number of pumps connected using τ equal to 8760 hours (1year). As mentioned before, each pump-set is required to contain one duty and one standby pump. They were connected in parallel. In equation (6), the more the components connected in a parallel network, the higher the reliability of the network. In Table 6, the reliability of the network increases with the number of pumps connected. There is a large increase in reliability in changing from one pump to two pumps in parallel, but the increase is not significant when two pumps were changed to three or four pumps in parallel.



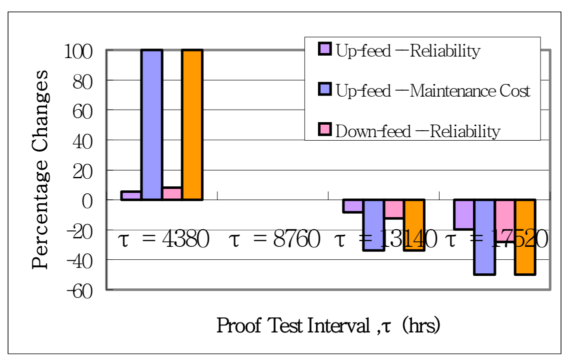
Graph C: Reliability of single and pump systems

4. CONCLUSION

4.1 Selection of Proof Test Interval

From the previous results, the shorter the proof test interval, the higher the reliability. But the proof test interval (τ) is 8760 hours (one year) for the fire protection in Hong Kong. According to the Fire Services Department requirement, the test interval is that every fire service system should be checked and tested every year. The main reason for not shortening τ is the increase in cost would be very high while the increase in reliability might not be significant.

Graph C and D were drawn using the data in Tables 1, 4 and 5 about the reliability and maintenance cost of the up feed and down feed systems with different proof test intervals. These two graphs were used to compare whether it is necessary to shorten the proof test interval to raise the system reliability as life safety is very important, or to increase the proof test interval to save more money.



Graph D: Percentage changes of reliability & MC

In Graph C, the increase in reliability for both the up feed and down feed systems when compared to a single pump is the highest at τ equal to 8760 hours (1 year). They are both above 0.9 (90%). It is also possible to change τ to 13140 hours (1.5 years) as around 30% of maintenance cost could be saved, as in Graph D. The reliabilities are around 0.8 to 085 (80% to 85%), which is acceptable. It is not recommended to use τ equal to 17520 hours (2 years). Even though a large amount of money could be saved, the reliability of the systems, especially the down feed system, is too low. In Graph D, the difference between the percentage changes in reliability and maintenance cost is the highest at τ equal to 4360 hours (0.5 year).

A pump system with reliability around 0.9 (90%) is highly accepted. The fire pumps would just be actuated during a fire. The probability of a building having a fire is very low. And so the probability of a fire pump being actuated would also be very low. It is not necessary to raise the reliability of the pump system up to around 0.95 or even higher by using a large amount of money. After comparing the cost and effectiveness of the systems using different proof test intervals, τ equal to 8760 hours (1 year) is recommended.

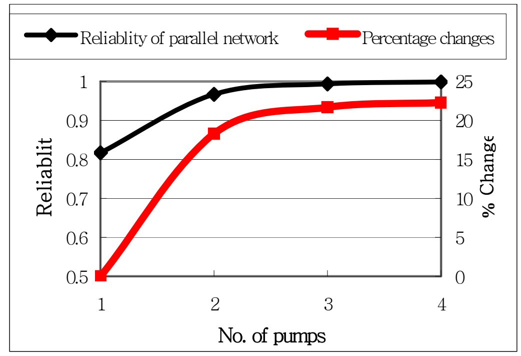
4.2 Reliability of Water Supply

In Table 4, the reliability of the up feed system is higher than that of the down feed system due to fewer components. But the reliability of water supply of the down feed system may be higher. The roof tank could still supply water down to the floor by gravity even when the fire pumps were out of order. But the water pressure at several floors below the roof might be not sufficient. After receiving a fire call, the firemen would arrive within 6 minutes in built-up areas and within 9 to 23 minutes in areas of dispersed risks and isolated developments [16]. The roof tank should have sufficient water supply before the arrival of the firemen.

4.3 Parallel Network

Graph E was plotted using the result in Table 6. There is a sharp increase (18.3%) of reliability when one pump was changed to two pumps in parallel. Using one duty and one standby pump in a pump-set is the basic requirement by the Fire Services Department. The increase is not significant (3.4%) when two pumps were changed to three. Increasing to four pumps in parallel just resulted in 0.6% increase in the network reliability. Adding one more pump to the network would cost 100% more. After comparing the cost and effectiveness of the network using different number of pumps, two pumps in parallel is recommended.

The existing requirements for the proof test interval and fire pump configurations in Hong Kong are already quite effective when considering about the cost. It is not necessary to have big changes to them.



Graph E: Reliability and percentage changes of different number of pumps

REFERENCES

1. T.F. Barry, Risk-informed, performance-based industrial fire protection, Tenessee Valley Publishing, USA (2002).
2. ANSI.IEEE Standard 500 P & V, Reliability data for pumps and drivers, valve actuators, and valves, The Institute of Electrical and Electronics Engineers Inc, NY, USA (1984).
3. 2 data files from Electrical and Mechanical Services Department (EMSD), Hong Kong.
4. W.K. Chow, "Reliability study on sprinkler system to be installed in old high-rise buildings", International Journal on Engineering Performance-based Fire Codes, Vol. 2, No. 2, pp. 61-67 (2000).
5. K.C. Hignett, Practical safety and reliability assessment, E & FN Spon, London, UK (1996).
6. E.J. Henley and H. Kumamoto, Reliability engineering and risk analysis, Englewood Cliffs, N.J., Prentice-Hall (1999).
7. R.D. Leitch, Reliability analysis for engineers, Oxford University Press (1995).
8. M. Modarres, M. Kaminskiy and V. Krivtsov, Reliability engineering and risk analysis, Marcel Dekker (1999).
9. N.J. McCormick, Reliability and risk analysis, Academic Press, Chapter 7 (1981).
10. Code of Practice for Minimum Fire Services Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment, Fire Services Department, Hong Kong June (1998).
11. L.T. Wong, Fire Services, Lecture notes 2002/2003.
12. F.S.D. Circular Letter No. 4/96, Fire Services Department, Hong Kong.
13. B.S. Dhillon, Series on industrial & systems engineering, Vol. 1, World Scientific Publishing Co. Pte. Ltd, Singapore (2003).

14. Y. Qi, "A study on the reliability of fire water supply system in high-rise buildings", Fire Technology, Vol. 38, No.1, pp. 71-79 (2002).

15. ASTM International, Standard practice for measuring life-cycle costs of buildings and building systems, information handling services, E917 (1999).

16. Fire Services Department Website: http://www.info.gov.hk/hkfsd/home/