Research on Safety Assessment Indicators of Gas Extinguishing System for Urban Railway Transportation

Fangchen Mei [1,*], Chong Lei [1], and Jihao Xia [1]

[1] China Railway Si yuan Survey and Design Group Co, LTD, Wuhan 430063, China

* 007320@crfsdi.com

Abstract. Gas fire extinguishing system as a more widely used system in urban rail transit, its safety is related to the safety of passengers, lives and property. At present, there are few studies on the safety of gas fire extinguishing system, and there is no special standard to guide. In order to improve the safety of the subway gas fire extinguishing system, through a number of operating companies and manufacturers to conduct on-site research, and the use of theory and data analysis and other methods of gas fire extinguishing system safety indicators have been studied. Reliability analysis is carried out by using Fault Tree Analysis, and on this basis, the safety evaluation of the system is further quantified by identifying and analyzing the hazards of the gas extinguishing system and rating the risk of the system by using semi-quantitative method. The results show that the average working time index of the gas extinguishing system before hazardous failure is 173 years, and the average non-hazardous failure time is 173 years.

Keywords: Gas fire extinguishing; RAMS; Security; urban railway; fire control.

1. Introduction

With the continuous development of urbanization, fire prevention work is also facing serious challenges. In recent years, the number of fire accidents has been increasing year by year, and the importance of fire safety management work has been increasingly presented. Subway is one of the more important modern transportation, but it is located in the underground. Once a fire occurs, it is very easy to cause major casualties and property damage. Gas extinguishing is a commonly used of fire protection in subways, and few studies have been conducted to analyze its safety. Among them, Pilikai1designed a PLC-based electrical control system to reduce the probability of mis-spraying of the gas extinguishing system. Huang Xuguang2 proposed to set up multi-protection zones in data centers so as to reduce the operation and maintenance costs of gas cylinders.

According to the national standard GB/T 21562-20083, the safety parameters include the average non-hazardous failure time MTBF (H), hazard rate λ d (t), etc., but the standard does not specify the calculation methods of MTBF (H) and hazard rate. Meanwhile, GB/T 16855.1-20084, the system safety indexes include the average working time MTTFd before the occurrence of hazardous failure, and the life time when the probability of non-hazardous failure is 90% B10d. In principle, the safety parameters including the average non-hazardous failure time MTBF(H) and the average working time MTTFd before the occurrence of hazardous failure are equivalent, so the safety parameters can be calculated in accordance with the GB/T 16855.1-2008, and the average working time of the system can be calculated in accordance with the GB/T 16855.1-2008 to calculate MTTFd, that is to say, the average non-hazardous failure time MTBF (H).

The safety requirements should be compared with the safety objectives and safety policy of the rail transit authorities, and at the same time can be based on relevant research and data analysis to determine the overall safety index requirements for rail transit gas fire extinguishing system.

2. Reliability index analysis of gas extinguishing system

Gas extinguishing system safety index analysis is limited to be based on the reliability index analysis, the urban rail transit gas extinguishing system for Fault Tree Analysis, to get the fault tree shown in Figure 1.

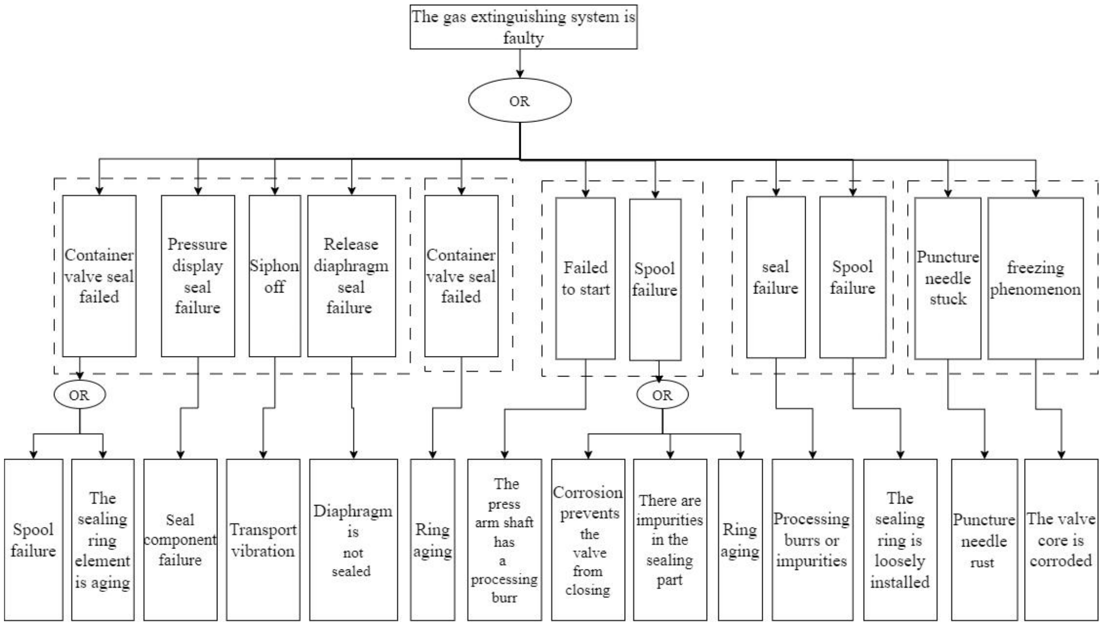
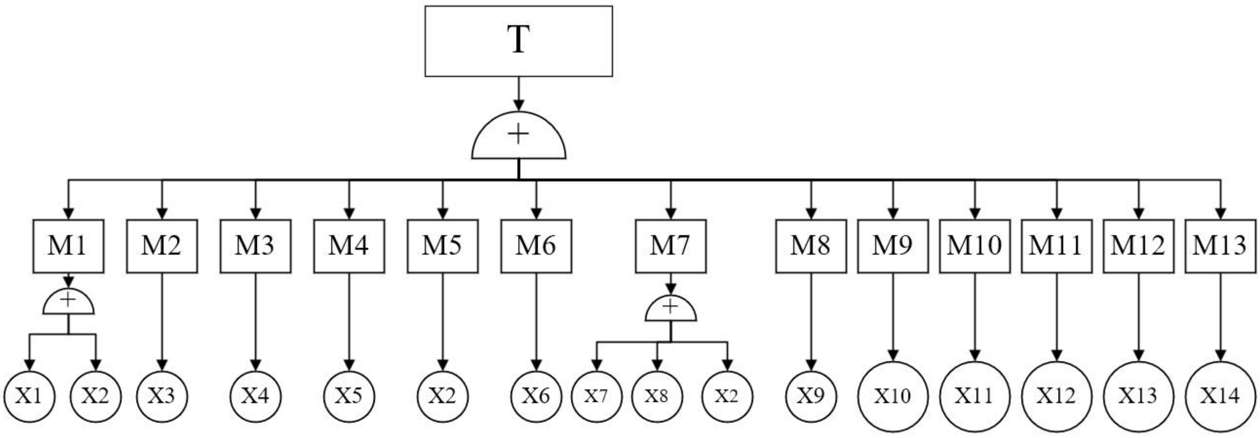


Fig 1. Fault tree analysis of gas fire extinguishing system



(a) Equivalent fault tree

① Minimum cut set/path set

The Boolean operation of this fault tree is as follows:

T= M1 +M2 +M3 +M4 +M5 +M6 +M7 +M8 +M9 +M10 +M11+M12 +M13

=X1+X2+X3+X4+X5+X2+X6+X7+X8+X9+X2+X9+X10+X11+X12+X13+X14

The fault tree has 14 minimum cut sets , so that the order of structural importance of each basic event of the fault tree is:

X2> X1=X3=X4=X5 =X6=X7=X8 =X9=X10 =X11=X12= X13= X14

② Probabilistic importance analysis

Probabilistic importance refers to the degree to which the change in the probability of occurrence of the basic event Xi affects the change in the probability of occurrence of the top event.

Based on the data of 1, it can be assumed that:

q1=q2=q3= q4= q5=1.97/104h，

q6=5.41/104h，

q7=q8=q9= q10=0.78/104h。

q11=q12=q13=q14=1.99/104h。

Thus, the probability of occurrence of the top event is:

qT = 26.34/104h

Probabilistic importance of the basic event IGi= ∂ qT/ ∂ qi, where IGi is the probabilistic importance of event Xi, then:

IG1=(1-q2)(1-q3)(1-q4)(1-q5)+(1-q6)+(1-q7)(1-q8)(1-q10)+(1-q11)(1-q12)(1-q13)-(1-q2)(1-q3)(1-q4)(1-q5)(1-q6)(1-q7)(1-q8)(1-q9)(1-q10)(1-q11)(1-q12) (1-q13)=0.99996135

The same goes for:

IG1 = IG2= IG3= IG4= IG5=0.99996135

IG6= 0.99999967815

IG7= IG8= IG9= IG10=0.999969978

IG11= IG12= IG13=0.999969978

The result shows that Seal ring aging failure will have a great influence on the frequency of system failure.

③ Critical importance analysis

Critical importance (also known as critical importance) of a basic event measures the importance of the basic event from the dual perspectives of sensitivity (also known as probability importance) and self-occurrence probability. The greater the critical importance is, the greater the influence of the change rate of the probability of the basic event on the change rate of the probability of the top event is. In this case, reducing the probability of the basic event has the most obvious effect on reducing the probability of the top event. When the critical importance of a certain bottom event is small, but its probability importance is large, it indicates that the occurrence probability of the bottom event maybe small, and it maybe difficult to reduce the occurrence probability of the bottom event.

However, due to the low failure rate of the Gas extinguishing system, it is more difficult to continue to reduce its failure probability, and it is necessary to further consider the critical importance ILi =IGi qi/qT, then

IL1= IL2= IL3 = IL4= IL5 =0.6581913

IL6=0.987316297

IL7= IL8=IL9= IL10=12.5056358

IL11= IL12=IL13=0.658191256

Reliability analysis for the weak link of the system components, the weak link of the system is the fire extinguishing agent bottle group, driving gas bottle group, selective valve and electromagnetic drive device, and the weak link belongs to the series relationship, the logic block diagram shown in Figure 2.

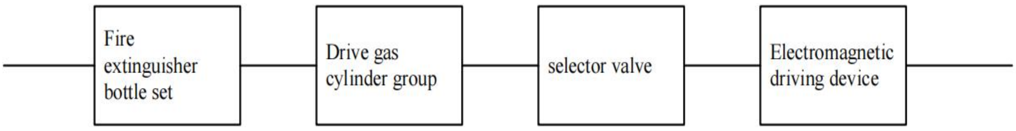


Fig 2. Reliability logic block diagram

Assuming that the life of each key component follows an exponential distribution, the failure rate of each key component can be calculated based on the following equation.

$$R(t) = \exp(-\lambda t) \qquad (1)$$

Where: R(t) is the reliability, t is the average failure time, and λ is the failure rate (times/unit time). Meanwhile, combined with the research results, the reliability of each key component of the gas extinguishing system at 54 months is shown in Table 1.

character radical	Fire extinguishing agent bottle set	Drive gas cylinder set	selector valve	Electromagnetic type drive
reliability	0. 9894	0. 9712	0. 9958	0. 9893

Failure rate λ (10-4 /month)	1. 97	5. 41	0. 78	1. 99

Table 1. Reliability of key components of gas fire extinguishing system

Based on the above table and logic block diagram, it can be concluded that the failure rate of the fire extinguishing system is 1×10-3/month, while the reliability function of this fire extinguishing system with respect to the lifetime is:

R extinguishes fires (t)= exp(-λt)

Solving the equation when R extinguishes fires (t) = 0.9yields, t = B10 = 104months.

This results in a demand for reliability indicators for gaseous fire extinguishing systems, as shown in Table 2.

Table 2. Reliability requirements of gas fire extinguishing system

Reliability indicators	Research and Data Analysis
Failure rate λ	1×10-3 /month
Mean Time Before Failure MTTF	986months
Life time B10 at reliability 0.9	104months

The above gas extinguishing system is further decomposed to obtain the secondary subsystem of gas extinguishing system, and the logical block diagram is shown in Fig 3. At the same time, the reliability of the secondary subsystem is assigned using the ARINC method, which is the failure rate based on the failure rate of equal proportional allocation of the failure rate, and the reliability index after the allocation is shown in Table 3.

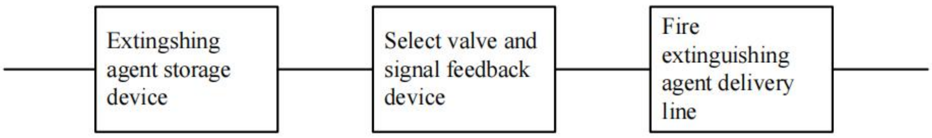


Fig 3. Reliability block diagram of primary system composed of secondary subsystem of gas fire extinguishing system

Table 3. Reliability index of secondary system of gas fire extinguishing system before and after distribution of reliability index

Secondary systems	Pre-allocation lapse rate (/month)	Distribution factor	Post-allocation lapse rate (/month)
Fire extinguishing agent storage devices	1×10-3	0. 33	0. 33×10-3
Selector valves and signal feedback devices	1×10-3	0. 33	0. 33×10-3
Fire extinguishing agent piping	1×10-3	0. 33	0. 33×10-3

3. Analysis of safety indexes of key components of gas extinguishing system

Based on the analysis in section 2, when the reliability of gas extinguishing system is 0.9, the life of gas extinguishing system B10 is 104 months. According to GB/T 16855.1-2008, based on the gas extinguishing system reliability index B10, the average number of cycles of the gas extinguishing system up to the time when 10% of the components have a dangerous failure B10d is converted:

B10d =2×B10 =2×104months =208months

Based on B10d for gaseous fire suppression systems, the mean time to failure MTTFd before the first hazardous failure of the system is derived as

$$MTBF(H)=MTTFd=B10d/(0.1\times nop)=208\times 24\times 30/(0.1\times 365\times 24)=170years \quad (2)$$

Where: 0.1 is the correction factor, and nop indicates the average annual working hours of the fire extinguishing system, i. e. 365 days/year×24 h/day = 8640 h/year.

Meanwhile, the hazard rate λd can be deduced from B10d by assuming that the non-hazardous failure time obeys an exponential distribution, and that the hazard rate λd is a constant.

$$Rd\ extinguishes\ fires\ (B10d)=exp(-\lambda dB10d)=0.9$$

When Rd extinguishes fires (B10d)= 0.9 and B10d = 208 months, solving the equation yields λd = 5. 0654×10-4 /month, as shown in Figure 4.

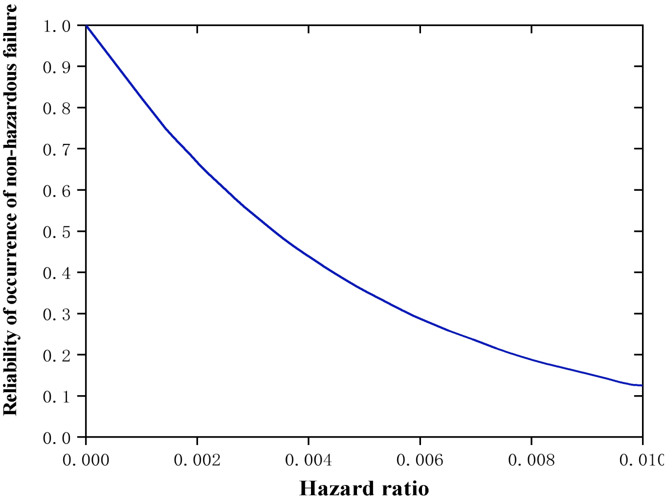


Fig 4. Plot of reliability as a function of hazard rate for the occurrence of non-hazardous failures of gas extinguishing systems6

In summary, the gas fire extinguishing system system safety requirements indicators are shown in Table 4.

Table 4. Safety requirements for gas extinguishing systems

Security Indicators	Against rail transit requirements	Research and Data Analysis
Life at 90% probability of no hazardous failure B_{10d}	/	208 months
Mean Time To Function Before Hazardous Failure $MTTF_d$	/	170 years
Mean Time Between Hazardous Failure (MTBF) (H)	/	170 years
Hazard rate λ_d	/	5.07×10^{-5} /month

4. Safety Assessment Study on Key Components of Gas Extinguishing Systems

By identifying and analyzing the hazards of the gas extinguishing system and using the semi-quantitative method to rate the system risk, and based on the allocation of reliability and the allocation of repairability, the safety evaluation of the system is further quantified. It is derived that firstly according to the reliability allocation after the first level system reliability function is:

$$R_{I}(t)=\exp(-(\lambda_{II,1}+\lambda_{II,2}+\lambda_{II,3})t) \quad (3)$$

Where, based on the secondary subsystem reliability λ Ⅱ=0. 33×10-3 /month in λ Ⅱ, solving the equation when the primary subsystem RI(t)=0.9, yields, t=B10I=105 months, as shown in Table 5.

Table 5. Reliability function results of gas extinguishing system

t (months)	Tier 1 System Reliability $R_I(t)$
50	0. 951
60	0. 942
70	0. 932
80	0. 923
90	0. 914
100	0. 905
105	0. 900
110	0. 896

Based on the gas extinguishing system primary system reliability index B10dI, the discounted B10dI for the primary system is: B10dI=2×B10I=210 months.

Based on B10dI for the primary system of a gas extinguishing system, the mean time to operate the system before a hazardous failure occurs MTTFdI , the mean time to non-hazardous failure MTBF(H) is

MTBF(H)=MTTFdI=B10dI/(0.1×nop)= 210×24×30/(0.1×365×24)=173 years

Where: 0.1 is the correction factor, and nop indicates the average annual working hours of this fire extinguishing system, 365×24 h.

Therefore, after the RAM allocation, the gas extinguishing system safety index is to meet the system safety requirements.

Table 6. Safety requirements for gas extinguishing systems

Security Indicators	System Security Requirements	System security metrics after RAM allocation	reach a verdict
B_{10d}(hours)	208 months	210 months	eligible
$MTTF_d$ (years)	170 years	173 years	eligible
MTBF (H) (years)	170 years	173 years	eligible

5. Conclusions

Through on-site research and numerical analysis, the average working time index of urban rail transit gas extinguishing system before hazardous failure is obtained as 173 years, and the average non-hazardous failure time is 173 years.

Through the analysis of safety indexes of key components of gas fire extinguishing system and safety assessment research, a RAMS assessment method of gas fire extinguishing system is provided, which is helpful for guiding the optimization of the design of gas fire extinguishing system for urban rail transit and further safeguarding the operation safety of urban rail transit industry.

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