Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2019, 60 (132), 177–183
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/387

Received: 21.08.2019
Accepted: 24.10.2019
Published: 18.12.2019

Selected issues of reliability and availability in marine vessel fire alarm systems

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Key words: reliability, safety, protection, availability, fire alarm system, human factor

Abstract

Today, every industry is striving for the highest efficiency and best economic results possible, with the greatest possible competitiveness. But in maritime affairs, human safety and environmental protection are the foundations of sustainability. To achieve this, marine systems must be reliable, high quality and easy to maintain. Because of this, reliability has become an important factor in safety, which remains relevant throughout the lifetimes of ship systems, including fire alarm systems. In this paper we address a number of issues connected with the reliability – and 'availability' of these systems. Firstly, ship fire alarm systems consist of various components whose individual reliability affect the system's overall reliability. Discussions of reliability in ship fire alarm systems normally focus on the length of a system's useful life or performance during design-based fire events. In addition to the reliability of systems, their availability for use is also crucial given the possibility that the system may need to operate at any point in time.

Introduction

The effectiveness of a marine vessel's fire alarm system can greatly impact the safety of the lives on-board. It is important to know that the system is reliable, including that its components are functionally accurate. Ensuring the reliability of marine fire alarm systems throughout their useful lives requires quality processes in equipment manufacturing, system design, programming, on-board testing, registry testing, and maintenance.

The reliability of marine vessel fire alarm systems

Early detection of fires plays a crucial role in extinguishing them and preventing them from spreading. The development of fire alarm technology has been fueled by past fire incidents that resulted in major material losses and worse, human casualties. In recent decades, the development of fire alarm detectors, by integrating them with microelectronic and information technologies, has achieved a high degree of system autonomy while increasing both reliability and availability.

We define reliability here as a function of time $R(t)$ yielding the probability that a device, such as a fire alarm system, will operate satisfactorily for a certain amount of time t, correctly without failure; that is, the reliability is determined by the total number of failures of the fire alarm system within an estimated time interval. According to the SFPE Fire Safety Manual, "reliability" is the ability of a product or system to operate under certain conditions for a specified period of time or series of cycles (Modarres & Joglar-Billoch, 2002).

The main measure of the reliability of any system, including fire alarms, is their availability $A(t)$, as defined by British Standard BS 4778: "the ability of an element or system to perform its required function at a specified current time or above a specified period of time" (BS 4778:Part 2, 2002).

In summary, fire alarm system reliability signifies time of useful life and performance during fire events. Also, according to the manual, ensuring the reliability of fire alarm systems throughout their useful lives requires quality processes in the production of equipment and system design, proper installation, and adequate programming, testing, and maintenance.

Today's techniques for determining reliability can pre-determine the service life of a fire alarm system and its components. The mean time of failure can be calculated in the same way as the mean value of failure, which is important when maintaining the ship's fire alarm systems. In addition, a reliable fire alarm system must be able to signal any failure in a timely manner. Different types of fire alarm system failures include:

- complete or catastrophic component failures,
- failures due to their gradual degeneration,
- failures due to wear and tear on components during operation.

Each of these types of failures can be classified as either:

- primary or independent,
- secondary or dependent.

A diagram showing fault intensity across the life of a device is shown in Figure 1.

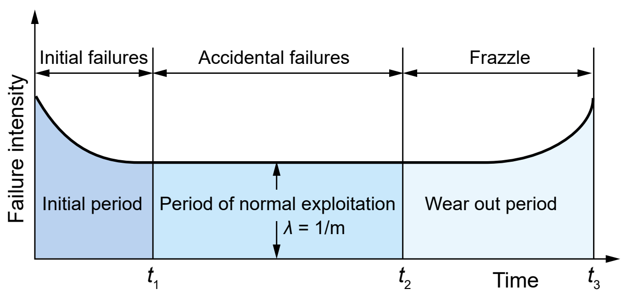

Figure 1. Fault intensity function

Figure 1 shows the failure rate during each of three fault phases:

- the first phase – initial period of operation (t_1),
- the second phase – period of regular exploitation of the system ($t_2 - t_1$),
- the third phase – weariness of the system and tears ($t_3 - t_2$).

In the first phase, during the testing of a system and its components, and its commissioning, failures occur more frequently, with a tendency to gradually settle down, as factory and assembly errors are eliminated. The second phase, the standard operating life of the system, is generally expected to witness the fewest failures. After a successful working life, the system and its components slowly lose their abilities to function properly and the system becomes unreliable, requiring replacement of worn out components.

In addition to on-board periodic testing of the fire alarm system, which is carried out at least once a year, the condition of the system is also periodically tested by the flag carrier's registration companies for the purpose of obtaining the system's and ship class's certificate of safety, in accordance with international standards and rules.

It is important to note that the port authorities of any state have the right to request the testing of a ship fire alarm system and, in case of malfunction, to prohibit the entry of a ship into its port of destination.

Counteracting the reliability of fire alarm systems are several factors, including failure due to software elements, failure due to human factors or operating documents, and failure due to weather conditions and other environmental factors. According to one of the three basic probability theorems, the sum of reliability $P(q)$ and unreliability $P(\bar{q})$ equals one:

$$P(q) + P(\bar{q}) = 1 \tag{1}$$

One of the most commonly used methods of increasing the reliability of ship fire alarm system is certainly the redundancy method, which has been strictly applied on passenger ships since 2010, in line with the SOLAS regulations for safe return to port (IMO, 2006; Bistrović et al., 2014). The redundancy method is implemented with 'dual systems,' in which a functional component remains in operation, filling the role of a defective or deactivated component while the system is restored or repaired. I.e., system operation does not have to be interrupted for maintenance intervention on a failing component, making system reliability completely independent of its time operating, the "*t,*" of the system. Suppose a short time "*t*" is required to replace a defective component. While the backup component works, the dual system can schedule to replace the defective component only if it fails during a short time (Lovrić, 1989). The probability that this happens $Q(t)$ is given by:

$$Q(t) = 1 - e^{-\lambda t} \tag{2}$$

If "*t*" becomes infinitesimal, that is, if replacement is made instantaneously, this expression becomes zero, which means that the system will never schedule replacement. While it is not realistic to assume that the time required for replacement will ever be zero, it can still be made relatively short. The reliability of such a dual system depends then on the chances that the other component will fail over the time "t" from the failure of one component until the completion of its replacement or repair:

$$R(t) = e^{-\lambda t} \quad (3)$$

Thus, the reliability of the system becomes independent of its hours operating and depends only on the short time "t" required to replace or repair a component.

Using this probability theorem, the unreliability of fire alarm elements can be represented by the equation:

$$Q(t) = 1 - R(t) = 1 - e^{-\lambda t} \quad (4)$$

where:
Q – unreliability,
R – reliability,
λ – proportional failure rate,
t – time.

From this it can be concluded that, while the fire alarm system is new, its reliability is high and the probability of failure is low ($t \rightarrow 0$, $R = 1$), however, as the life expectancy of an on-board fire alarm system comes to an end ($t \rightarrow \infty$, $R = 0$), reliability decreases and unreliability increases while increasing the likelihood of a fire alarm system and its components.

Redundancy of passenger ship systems, including the fire alarm system (Figure 2), provides reliability, security, and the ability of the system to continue its deadlock avoidance function even when some components are subject to new regulations or failures (Bistrović et al., 2014).

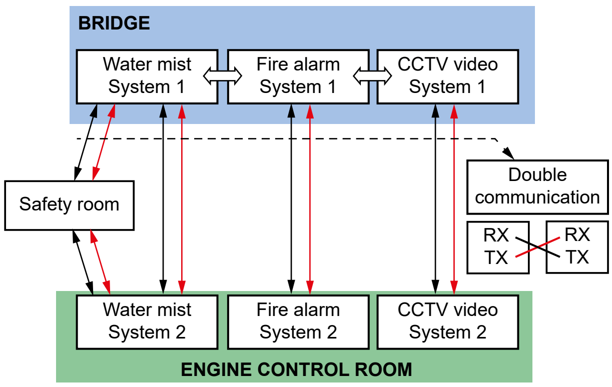

Figure 2. Display of high redundancy, according to SOLAS regulations, for safe return to the port

Figure 2 shows that passenger ships sailing since 2010 must have two fire alarm systems that communicate with each other via a dual communication line. If one of them fails, the system will still function normally, while giving an error message. Also, if one fire alarm system fails, the other must continue to operate normally even if the system's fault alarm does not function properly.

Availability of marine vessel fire alarm systems

Like reliability, availability is the likelihood that a component or system performs its required function at a predetermined point in time or beyond a specified period of time when, it is operated and maintained as intended.

To calculate availability $A(t)$, the expression below is used:

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t} = A_s + A_{tr}(t) \quad (5)$$

or:

$$A(t) = \frac{\mu}{\lambda + \mu} \quad (6)$$

where:
μ – intensity of repair,
λ – failure intensity.

Accordingly, the availability $A(t)$ of a fire alarm system can be determined by the expression:

$$A(t) = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \quad (7)$$

where:
MTBF – mean time between failure;
MTTR – mean time to repair – that is, until the components are restored.

As a rule, there must be a reserve on-board holding at least one copy of each module of the central fire alarm system. A number of each detector type must also be in the reserve.

MTTR on a ship depends on three factors:
- type of fault,
- number of spare parts on-board,
- crew training in proper handling of the system.

The success of the fire alarm system requires the seamless functioning of many interconnected components. Figure 3 shows the fire detection and alarm fault tree, divided into six subsystems, and the following:
- a map of detector faults,
- a map of faults of alarm system components,
- a map of errors signaling subsystem communications,
- a map of faults of the auxiliary control subsystems,
- a map of power errors,
- a map of false alarms.

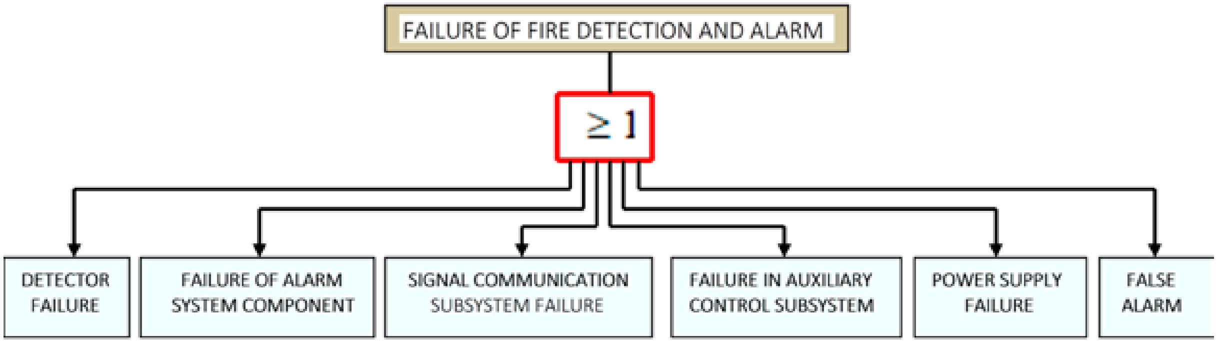

Figure 3. Map of fault detection and fire alarm divided into six subsystems

Each of the six subsystems can further be displayed with its own fault tree. When we know that λ is the fault index and X the number of failures, T the time interval to failure can then be estimated as the error rate of the fire alarm system:

$$\lambda = \frac{X}{T} \tag{8}$$

The availability of each system, including the fire alarm system, is the likelihood that the system works smoothly, performing functional tasks at any given moment. The basic factors that go into availability are the properties of the system itself, the environment in which it operates, and the quality of maintenance. The literature describes several types of availability, such as 'own availability,' 'reach availability,' and 'operational availability.'

In Figure 4 are shown the links between reliability, maintenance, and availability (Mihai et al., 2010).

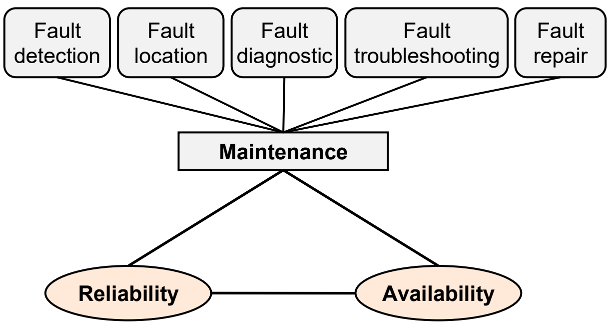

Figure 4. Connections between reliability, maintenance and availability

Figure 4, underlines the fact that the reliability of a system is characterized by a set of measures that give information on the performance of the system functionality over a period of time.

'Own availability' is an indicator of the readiness of the system itself, and speaks to its reliability. The assumption of self-availability is the proper operation of the system until failure or shutdown and repair, when the conditions for repair obtain.

'Reach availability' includes downtime, in addition to repair and maintenance time, and is calculated using the equation:

$$A_0 = \frac{\text{MTBM}}{\text{MTBM} + \overline{M}} \tag{9}$$

where:

MTBM – mean time between maintenance,

$\overline{M}$ – average active maintenance time.

The average time between maintenance sessions is determined by the expression:

$$\text{MTBM} = \frac{1}{\lambda + f_p} \tag{10}$$

where

f_p – frequency of preventative maintenance.

The average active maintenance time is calculated as:

$$\overline{M} = \frac{\lambda \cdot \text{MTTR} + f_p \cdot \text{MPT}}{\lambda + f_p} \tag{11}$$

where

MPT – average preventative maintenance time.

Operational availability takes into account the total downtime due to required maintenance. It shows the availability of the system in a real work environment and is expressed as:

$$A_0 = \frac{\text{MTBM}}{\text{MTBM} + \text{MDT}} \tag{12}$$

where:

MDT – mean down time,

MTBM – mean time between maintenance.

It is usual to have the average downtime displayed and counted according to the expression:

$$\text{MDT} = M + T_C + T_L + T_A \tag{13}$$

where:
T_c – average waiting time for maintenance,
T_L – average logistic waiting time for maintenance resources,
T_A – average downtime for administrative reasons.

In order to calculate the total downtime due to system maintenance, it is necessary to take into account the total time, from the observation of a malfunction or system shutdown for preventive maintenance, until restoration of the system.

The problem of false alarms for the reliability of marine vessel fire alarm systems

False alarms from a ship's fire alarm system are defined as the activation of the detector when there is no indication of smoke or fire. We know that smoke detectors respond to the presence of smoke particles in the air, temperature detectors to ambient heat, and flame detectors to light. In order to reduce the number or percentage of false alarms and therefore increase the reliability, it is necessary to pay attention to the placement of detectors in a specific ship space. Common causes of false smoke alarms include ship ventilation, through which certain quantities of dust particles sufficient to cause false alarms gather in the smoke detector chambers. Therefore, it is necessary to avoid proximity to ventilators during installation.

Table 1. Sources of false alarms related to detection methodology

Smoke detector	Dust Exhaust gases of main engine, auxiliary engines Oils or grease on a hot surface Aerated water Cigarette smoke Accidental damage Detector error
Heat detector	Hot surfaces and high ambient temperatures such as in the accommodation spaces of fuel units, separator and incinerator spaces, and near boilers, main and auxiliary engine exhaust pipes, heated fuel tanks, etc. Detector error
Flame detector	Flash Arc Welding Autogenous cutting flame Cigarette ash Lighters Boat lighting flash Accidental damage Detector error
Manual detector	Inappropriate human action (e.g., activation of manual malicious call points) Accidental damage Detector error

Also, temperature detectors should not be placed near heat-emitting objects. In terms of flame detectors, today's technology has produced smart detectors that recognize false flames from real by covering the full range of colors visible to the human eye. Table 1 provides a list of possible sources of false alarms for different types of detectors.

It is important that ship fire detection systems are not sensitive to false alarm sources since reoccurring false alarms become a nuisance and suppression systems may be unnecessarily activated.

Human factors in reliability

Early detection of fires plays a crucial role in extinguishing them and preventing them from spreading. History is full of cases where the human factor has caused fires on ships. Human causes are known to account for 80% of maritime accidents (O'Neil, 2003). The relative causal factors of maritime accidents are shown in Figure 5, according to the UK Maritime Accident Research Unit (MAIB, 2003; Baker, McSweeney & McCafferty, 2002).

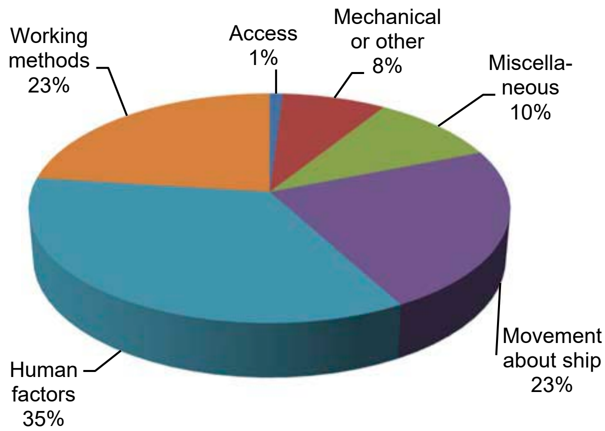

Figure 5. Causal factors of maritime accidents

Research has shown (Rothblum, 2000) that human error contributes to 84–88% of tanker accidents, 89–96% of ship crashes, and 75% of fires and explosions.

Any person involved in the chain, from designing, constructing, and navigating a ship or its components, to maintaining a ship fire alarm system can contribute to causing a fire on board. This applies in particular to poorly constructed fire alarm systems, inadequate maintenance, and poor training on the proper use of the system. The intensification of maritime trade over the past ten years has increased the potential for human error that could risk the safety of a ship.

Today, research into human factors as major causes of ship-related accidents, including fires and explosions, includes:

- identifying system hazards;
- estimating the frequency of each type of accident;
- estimating the consequences of an accident;
- calculating risk measures, such as the frequency of accidents of a particular type.

Human factors also include operational errors resulting from (Caridis, 1999):

- human physical, mental, and personal conditions,
- situational errors due to the design of the work environment,
- management problems,
- human-machine interface problems.

Application of multicriteria technology in fire detection reliability

The application of multicriteria fire detection technology began with the introduction of addressable analogy detectors. With the advancement of electronics and microprocessors within fire alarm systems, the first intelligent detectors were monitored and controlled by central units. The further development of microprocessors and electronics has enabled the creation of intelligent detectors, where data processing can be performed in the detector itself, independent of the central control unit.

It should be noted that much of the research on multicriteria fire detection technology has focused on the development of algorithms that use fuzzy logic and neural networks to classify events from fires to interference sources.

The idea of advanced phase logic (fuzzy logic) was first described by Professor Lotfi Zadeh of Berkeley University, California in 1960. Today, fuzzy logic has emerged as a profitable tool for managing and controlling various systems and applications. In the fire alarm system, the algorithms for light intensity, smoke density, humidity, and temperature, act as the phases of the input variable, on the basis of which the probability of fire occurrence is output.

Due to the possible errors and inaccuracies of fire detectors, many manufacturers of fire alarm systems use the logic of reviewing the detector signal three or more times; only after confirmation, the signal is allowed to continue. Fire detection can be based on the variables of smoke dimming (smoke density), smoke dimming rate, temperature, temperature change rate, and / or flame color. Most often, three values are assigned to these variables for detection – low, medium, and high. The higher the values of the variables, the more accurate the detection. Table 2 shows the ten phases of fire detection rules (Maksimović et al., 2014; Bistrović et al., 2014).

Table 2. Ten phase rules for detection of fire problems

Rule	Temp	Smoke	Light	Humidity	Distance	Output
1	L	L	L	H	Far	VL
2	L	L	L	H	Avg	VL
3	L	L	L	H	Close	VL
4	L	L	L	M	Far	VL
5	L	L	L	M	Avg	VL
6	L	L	L	M	Close	L
7	L	L	L	L	Far	VL
8	L	L	L	L	Avg	L
9	L	L	L	L	Close	L
10	L	L	M	H	Far	VL

In a fire detecting system, five input measures that can be taken are Temperature, Smoke, Light, Humidity, and Distance. Membership function for output is the probability of fire, having two variables: Very Low (VL), Low (L). For distance, we have three variables: Close, Average, Far. The other inputs include the variables: Low (L), Medium (M), High (H). These fuzzy inputs are then fed into inference, in which the fuzzy rule base manages inference to yield a fuzzy output (Kaur, Sethi & Kaur, 2014).

Conclusions

Fire alarm systems are composed of components. It is clear that the reliability of these components affects the reliability of the fire alarm system. Ensuring the reliability of a fire alarm system during its working life on-board a ship requires quality production processes for the system and its components from the beginning of production. It is unreasonable to expect as much as 100% system reliability during operation, because it is generally difficult to predict the frequency and types of possible failures. Knowing that the human factor sometimes reduces the reliability of systems due to inadequate maintenance, disinterest, and misbehavior, it is necessary to continually conduct training with an emphasis on the seriousness of proper handling and maintenance of the systems. It should also be emphasized that the reliability of the system is not complete without reliability of the power systems, both primary and secondary.

In the end, the impact of wear and tear on the reliability and availability of the system and its components over time cannot and should not be neglected.

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