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# Accident Cause Factor of Fires and Explosions in Tankers Using Fault Tree Analysis

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**Abstract:** Fire and explosion accidents occur frequently in tankers because they transport large quantities of dangerous cargo. To prevent fire and explosion accidents, it is necessary to analyze factors that cause accidents and their effects. In this study, factors that cause fire and explosion accidents were classified using the 4M disaster analysis method, and each factor's effect on the accident was analyzed using fault tree analysis (FTA). First, the unsafe tank atmosphere environment was identified as a primary cause of fire and explosion accidents in tankers, and the underlying causes of these accidents were investigated. The probability of underlying causes leading to primary causes was derived using an expert survey. The results showed that management and media factors had a greater impact on the unsafe tank atmosphere environment than human factors. To prevent fire and explosion accidents, it is necessary to ensure sufficient working and resting times for seafarers and compliance with procedures and work guidelines. A generalization of the results of present and future studies will enable the identification of the cause and preventive measures for fire and explosion accidents in tankers. Furthermore, this will reduce accidents in tankers and contribute to future safety management measures of ships and companies.

**Keywords:** tanker; fire and explosion accident; unsafe tank atmosphere environment; fault tree analysis method



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## 1. Introduction

### *1.1. Background*

Tankers generally refer to ships that are built or modified to transport large quantities of oils in freight space, and they include noxious liquid substance tankers and gas carriers, which transport liquid cargo in bulk [1]. Fires occur in various locations on ships, such as in the engine room and galley. As tankers transport oil and refined products, the possibility of fires occurring on these tankers is particularly higher than on other types of ships. Consequently, the International Convention for the Safety of Life at Sea and other international conventions have special fire safety requirements for tankers compared with ordinary dry cargo ships [2].

According to the 2020 yearbook of the Korea Maritime Safety Tribunal, 32 fire and explosion accidents on tankers occurred over the five-year period from 2016 to 2020, which is the largest number of fire and explosion accidents among merchant vessels [3]. Moreover, the volume of dangerous goods that were transported in ports in South Korea in 2018 was 534 million tons, which is approximately 21% higher than that in 2014. Fire and explosion accidents continued to occur, such as the accident of a chemical carrier that occurred in Ulsan Port on 28 September 2019.

To reduce fire and explosion accidents in tankers, efforts to identify the causes of accidents are required. Uğurlu [4] claimed that the root causes of fire and explosion accidents in tankers are combustible gas accumulation in the cargo tank, electric arcs, hot work, static electricity, and cargo. Similarly, the Ministry of Oceans and Fisheries [5] announced that recent fire and explosion accidents in tankers were primarily caused by unsafe tank atmosphere environments, such as oil vapor that was produced in the process of cleaning cargo tanks to remove residues after unloading dangerous cargo. Therefore, this study focused on the unsafe tank atmospheric environment that occurs before and after gas-freeing during the tank cleaning process. That is, most fire and explosion accidents in tankers occur because explosive gases, such as oil vapor and flammable gas, are exposed to a source of ignition in the atmosphere of the tank, from which the explosive gases have not been sufficiently removed. Accordingly, the South Korean government is making an effort to identify the causes of accidents to then prevent future ones through lessons learned, using education and training to prevent recurrence.

The research questions of this study are as follows:

Q1: What are the primary causes of tanker fire and explosion accidents?

Q2: What are the indirect causes of the primary cause?

Q3: What is the probability of an indirect cause inducing a direct cause?

Therefore, this study defines an unsafe tank atmosphere environment and considers most causes of explosion accidents in tankers as the primary cause. We then quantitatively identify the indirect causes of an unsafe tank atmosphere environment. The indirect causes are identified through a questionnaire survey of an expert group based on the IMO Res. A.884; it combines the classic disaster theory with the 4M (man, machine, media, and management) disaster analysis method of the National Transportation Safety Board (NTSB). The probability of the occurrence of an unsafe tank atmosphere environment, owing to underlying causes, was calculated using fault tree analysis (FTA). Based on the derived underlying causes and the probability of occurrence, this study suggests measures to reduce fire and explosion accidents in tankers, thereby contributing to the prevention of accidents, the preparation of safety management measures, and an improvement of the procedures for ships and companies.

### 1.2. Literature Review

Many studies have been conducted to analyze the causes of marine accidents. Organization, working conditions, and navigation environments are considered to be major factors in marine accidents [6]; however, recent studies have focused on human factors instead. Marine accidents caused by human factors have drawn attention since the capsizing accident of the Herald of Free Enterprise [7]. According to a report on marine accidents, approximately 80% of marine accidents were caused by human error [8]. Grech, Horberry, and Smith [9] reported that most marine accidents were caused by human errors, and they proposed improvements to prevent marine accidents, particularly focusing on the lack of situational awareness of seafarers. Psarros [10] suggested that marine accidents were caused by workplace conditions, physical and natural environments, procedures, technology, education, organization, management, and individual factors. Apostol-Mates and Barb [11] stated that human error is related to technology, the environment, organization, work practice, and the group. Fan, Zhang, Blanco-Davis, Yang, and Yan [12] stated that the three most effective recommendations to prevent marine accidents by human errors are information, clear command, and safety culture. Thus, previous studies have suggested improvements and preventive measures to mitigate human errors. However, unlike previous studies, the present study suggests improvements and preventive measures for the systematic investigation of human factors and considers the causes in terms of the 4M disaster analysis method and the domino theory.

Many studies related to fires in ships have been published. Chang and Lin [13] reviewed 242 accidents related to fires and explosions in storage facilities, and they categorized the causes of accidents into maintenance errors, operational errors, sabotage, equipment failure, natural disasters, and lighting. Celik and Cebi [14] applied a human factor analysis and classification system based on accident investigation reports for bulk carriers. Based on 121 container ship fire reports, Ellis [15] identified that 'deficiencies with packaging and containment' accounted for 66% of the failures that contributed to the release of dangerous goods. Baalisampang et al. [16] identified that mechanical failure contributed to 22% of fire and explosion accidents. Thus, many previous studies have been conducted based on accident reports. However, this study researched practical response measures to fire and explosion accidents by identifying indirect factors through a questionnaire survey of an expert group based on the IMO Resolution (Res A.884(21)).

In particular, a number of papers on tanker fire and explosion accidents have been published. Celik [17] emphasized that the competence and familiarity of shipboard personnel should be ensured to improve safety as a result of a study focusing on chemical tanker cargo explosions. Alexopoulos and Konstantopoulos [18] studied the factors of fire and explosion accidents in tankers by classifying them into engine room, cargo tank, accommodation area, etc. In particular, in the cargo tank, it was said that poor maintenance, improper operation of IGS, and cracks in the cargo tank in the loaded condition could be the cause, and in the ballast condition, the uncontrolled atmosphere and oxygen quantity within the tanks could be the cause. As such, it was analyzed that the causes of fire and explosion accidents of tankers were weaknesses in human factors and non-fulfillment of procedures. FTA is a systematic approach to evaluate the safety and reliability of a complex system, and it has the features of concision, visualization, and predictability. Consequently, many studies on marine accidents have been conducted using FTAs. Guan, Zhao, Shi, and Zhu [19] used an FTA to investigate the causes of and response measures to fires and explosions in the engine rooms of dual-fuel ships. Zhao-mei [20] qualitatively and quantitatively discussed the major causes of fires and explosions in crude oil gathering transport combination stations using FTA, and they suggested appropriate improvement measures. In particular, Hwang [21] developed a fault tree through accident factor analysis and calculated the risk of falling into the sea through a survey. Therefore, FTA is an appropriate research method that can be utilized to reveal the major causes of fire and explosion accidents and to investigate corresponding response measures. Hence, this study also uses FTA to analyze fire and explosion accidents in tankers and investigate countermeasures against them.

## 2. Methods

### 2.1. Domino Theory

As in previous studies, the human factors mentioned in the accident investigation report reveal only limited factors. Because there are many types of factor, there is a limit to using only the human factors mentioned in the accident investigation report. Therefore, this study intends to select factors by combining the IMO resolution and 4M. Heinrich's domino theory is a well-known theory of accident causes [22], and it has identified unsafe acts and conditions as the most prominent causes of accidents through the assumption that accidents and disasters occur in a chain. Heinrich's theory provides the advantage of defining the accident process; however, it focuses on unsafe acts and conditions and lacks management factors for accident prevention [23].

Bird systematized the domino theory and stated that the lack of control/management roles in Heinrich's theory caused the unsafe acts and conditions, which required removal and prevention [24].

Bird's domino theory can present management factor measures that focus on and manage the underlying cause that leads to the primary cause of an accident. Hence, this study applied this theory to the analysis of the underlying causes of unsafe tank atmosphere environments, such as flammable gas and oil vapor.

The underlying causes for the unsafe tank atmosphere environment were classified into 4M factors, which are used by the NTSB for accident investigation.

The 4M factors can be used to evaluate the causes of accidents and determine the relationships between the factors that generate the conditions leading to accidents [25].

The model used in this study, which is a domino model that applies the 4M factors to Bird's theory, is shown in Figure 1.

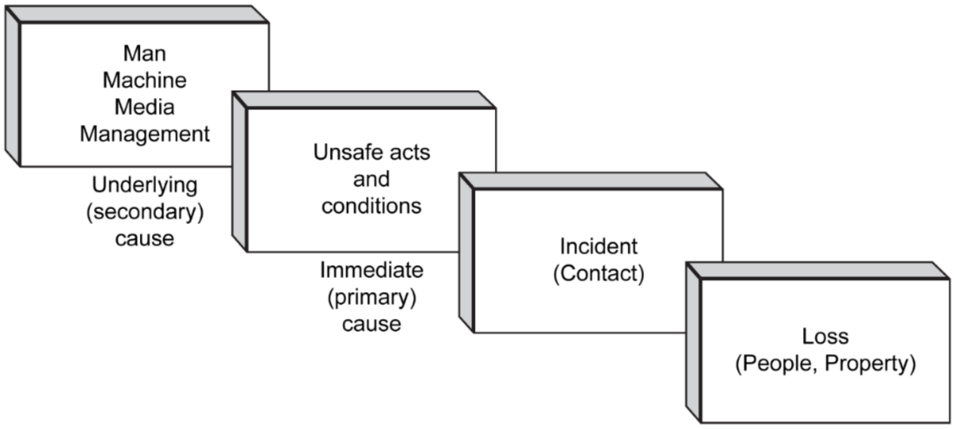


**Figure 1.** Domino sequence of accident causation theory (updated by author).

### 2.2. Fault Tree Analysis

The underlying causes that are classified into the 4M factors of Bird's domino theory are quantified using FTA. FTA is a representative method of system safety engineering that was first designed by Bell Labs in the U.S. in 1962 [26]. It is an analytical technique that systematically and scientifically performs accident prevention activities by creating a fault tree using logical symbols for the relationships between events for expected accidents in various industrial entities and factories and the defects or errors that cause such events. It then analyzes the fault tree deductively, quantitatively, and probabilistically, and it expresses the cause of accidents using a quantified probability [27].

This analysis method is characterized by performing deductive analysis from the top event, such as a disaster phenomenon, toward a basic event, which is the cause of the disaster that can no longer be divided. Thus, the structure of the accident can be identified simply by the main points of the causes of the accident written in detail, and the chain causes of the accident can be observed at a glance because they are displayed on a tree. Moreover, computer and statistical processing is possible because the causes of an accident are analyzed quantitatively, and a safety checklist can be created based on FTA.

We consider FTA to be a research method that can deductively and quantitatively suggest the cause of an unsafe tank atmosphere environment when the FTA for the underlying causes is conducted through an expert questionnaire survey. This is because disaster analysis by FTA can accurately schematize the relationships between the cause of disasters and their factors. It also enables deductive thinking, which leads to a better understanding of the dominant relationships between the factors [28].

The IMO Resolution (Res A.884(21)) about the 'factors influencing the accident cause during the investigation of marine accidents' addresses the underlying causes that correspond to the 4M factors. This resolution suggests that every marine accident is related to a human cause, and it is caused not only by human problems, but in combination with various factors [29]. The IMO Resolution (Res A.884(21)) stipulates that an investigation should be conducted in six categories: people, organization on board, working and living conditions, ship, shore-side management, external influences, and environment. Prior to the conduct of the survey on the expert group, a preliminary survey combining the 4M factor and IMO resolution was conducted to obtain the input of eight experts for verifying the validity of the survey items The expert group consisted of captains of tanker ship, superintendents of the shipping company, and instructors of maritime education institution with experience as chief officers of tankers. Based on this preliminary survey, items that were unrelated to the root cause leading to unsafe tank atmospheres were excluded, and some items were re-categorized. The underlying causes confirmed via the preliminary survey were identified and classified as shown in Table 1.

**Table 1.** Classification of items by 4M factors in consideration of IMO Res A.884.

| | Items of 4M Factors |
|---|---|
| Man factors | Lack of experience, knowledge, and skills of seafarers<br>Seafarers unstable mental and emotional state<br>Insufficient physical condition of the seafarers<br>Seafarers activities before accident |
| Machine factors | Availability and reliability of equipment to be used for work<br>Maintenance status of equipment to be used for work<br>Level of automation of the equipment to be used for the job |
| Media factors | Seafarers of various nationalities<br>Excessive overtime and insufficient rest time<br>Ship structure, such as work space structure<br>Type and condition of cargo loaded on the ship<br>Working conditions according to ship schedule |
| Management factors | Insufficient company safety management and management policy<br>Insufficient supervision of work management of companies and ships<br>No on-board training and drills for seafarers<br>Procedures and work instructions that do not reflect the latest regulations<br>Absence of tank cleaning work plan on ship |

Tanker fire and explosion (A1), which is the top event, can occur in various sub-events such as an unsafe tank atmosphere environment (B1) and bad maintenance and cracks in the cargo tank. The events are connected by a logical sum OR gate. However, because the object of this study is a fire and explosion accident owing to an unsafe tank atmosphere environment, the irresistible force is represented as a component of the FT diagram for fire and explosion, and it is not addressed. The sub-events of the unsafe tank atmosphere environment, which is an intermediary event of fire and explosion, were classified into categories C1–C4 according to the 4M factors. Additionally, each M was connected by a logical sum OR gate because each can be an underlying cause for the unsafe tank atmosphere environment.

According to the scope of this study, the occurrence of an unsafe tank atmosphere environment (B1) is defined as the primary cause, and the related 4M factors (C1–C4) are secondary causes. The detailed 4M factors that reflect the IMO Resolution were classified into tertiary causes (D11–D45), and they comprised the questionnaire for quantification. The tertiary causes are also connected to the secondary causes by logical sum OR gates, as shown in Figure 2.

*2.3. Calculating the Probability of the Occurrence of an Accident*

Boolean algebra is used to express or simply fault trees as equations. This method utilizes AND gates and OR gates of subsets comprising a particular set as a means of logical calculation. The use of subset probabilities refers to a method that calculates the probability of occurrence of a normal or intermediate event. If a fault tree is composed of many basic events, it is more efficient to divide the fault tree into a few partial fault trees, which can be analyzed before analyzing the total fault tree.

This fault tree is composed of AND and OR gates, and the probability of an event occurrence using the analytical method can be represented; this method assumes that basic events are statistically independent from each other.

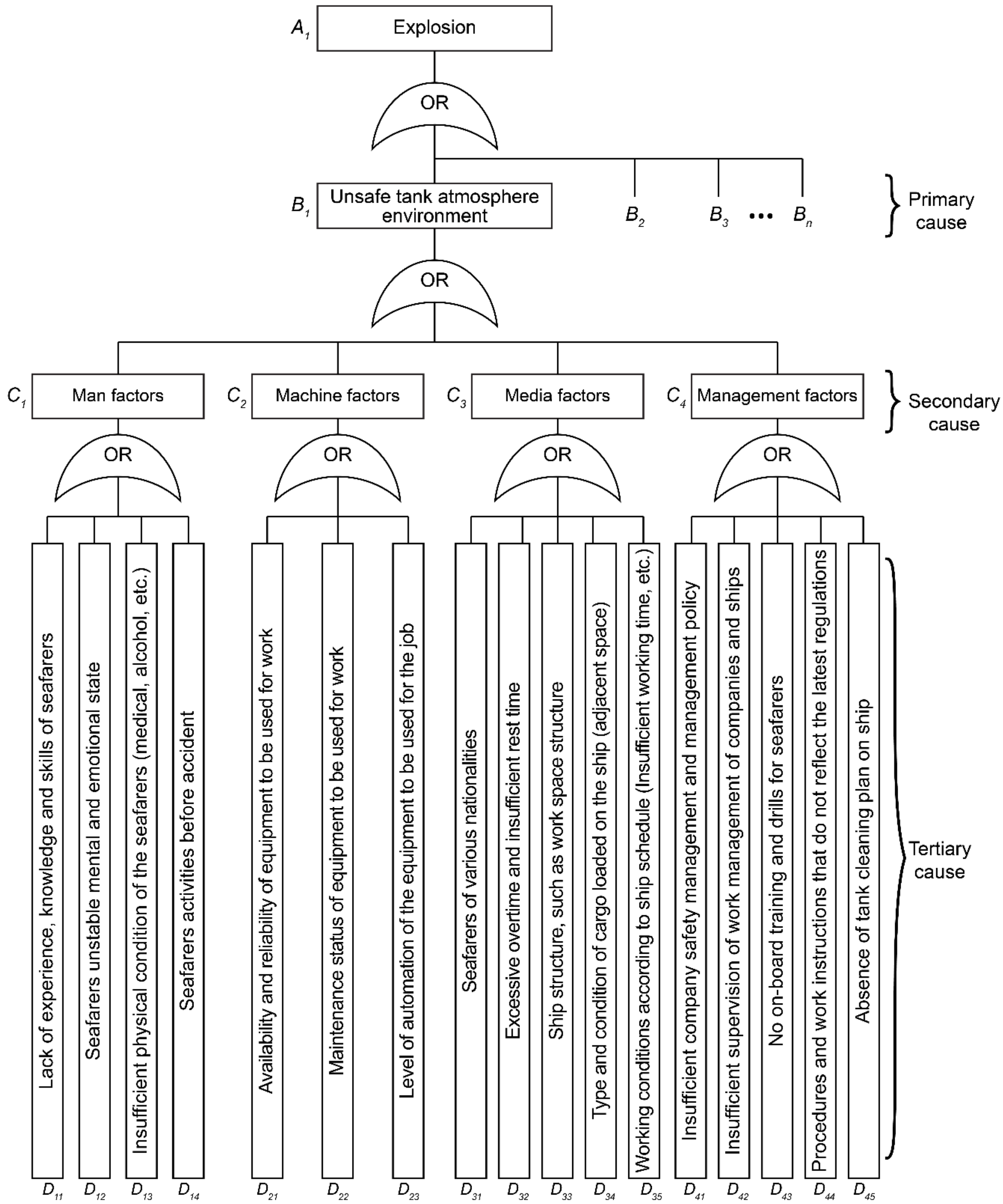


**Figure 2.** Fault tree diagram for analysis of explosion accidents caused by unsafe tank atmosphere environment.

A fault tree can always be converted to a fully equivalent minimum cut set, which can be considered as the root cause of a top event. Every cause that can lead to an unsafe tank atmosphere environment can be considered to be an OR gate. As shown in Table 2, the fundamental laws of Boolean algebra were applied, and all causes were reduced to a minimum cut set that can cause top events [30]. In the final analysis, every cause can lead to a top event and can be simply expressed.

**Table 2.** Boolean algebra fundamental laws.

| Laws | Formula |
|---|---|
| Commutative laws | X + Y = Y + X |
| Associative laws | X + (Y + Z) = (X + Y) + Z |
| Distributive laws | XY + XZ = X(Y + Z) |
| Laws of absorption | X + XY = X |

As shown in Figure 3, the probability of a fault tree connected to an OR gate can be calculated as follows:

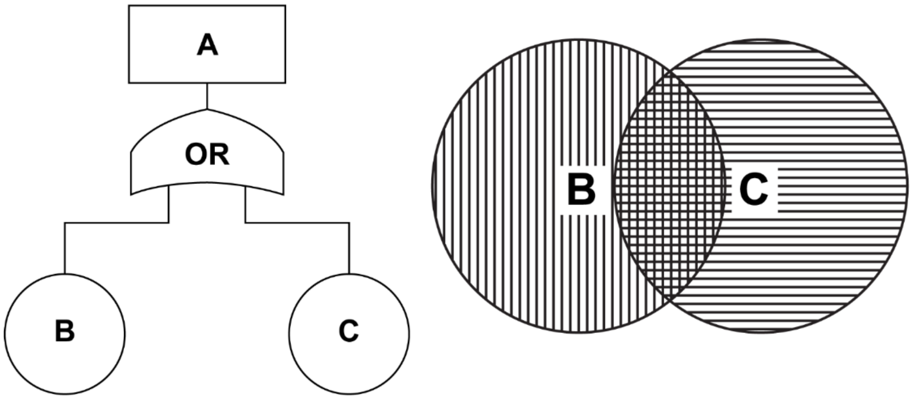


**Figure 3.** Logic of OR gate for fault tree analysis (FTA).

If $B$ and $C$ are independent events, equivalent to either Equation (1) or Equation (2).

$$F_A = F_B + F_C - F_B \cdot F_C$$

$$(\text{if } F_B = 1 - R_B \text{ and } F_c = 1 - R_c)$$

$$F_A = 1 - (1 - F_B)(1 - F_C) \quad (1)$$

or

$$F_A = 1 - R_A = 1 - R_B \cdot R_C = 1 - (1 - F_B)(1 - F_C) = F_B + F_C - F_B \cdot F_C \quad (2)$$

when combined using OR with $n$ basic events, it becomes Equation (3).

$$F_S = 1 - (1 - F_1)(1 - F_2) \cdots (1 - F_n) = 1 - \prod_{i=1}^{n} (1 - F_i) \quad (3)$$

where $F$ is the probability of an event, $R$ is the reliability of an event, and $n$ is the number of events.

## 3. Results

### 3.1. Survey Results

A questionnaire survey was administered to experts from ship management companies, shipping companies, educational institutions, and research institutes. The questionnaire asked the respondents to provide their personal information and to choose the detailed 4M factors (D11–D45) that cause an unsafe tank atmosphere environment (B1). To prevent 4M factor classification from affecting the responses, the 17 detailed factors were listed randomly for each respondent to avoid biased answers, and it was explained to the respondents that they could make single or multiple selections. The questionnaire explained that the focus of the survey was unsafe tank atmospheric environment.

Using an online survey tool, responses from 301 persons were collected for one month, from 1 to 30 April 2021. The respondents had tanker boarding experience of five years and eight months on average, and their duties on board varied between captain, navigation officer, engineer, and crew member.

The responses to the underlying causes of an unsafe tank atmosphere environment, which is the primary cause of tanker explosions, are listed in Table 3. The table also shows the number of responses and the ratio for the detailed causes according to the 4M factors.

**Table 3.** The results of the questionnaire on tertiary causes of explosion accidents, owing to unsafe tank atmosphere environment.

| 4M Categories | Tertiary Causes | Number of Responses | Ratio (%) |
|---|---|---|---|
| Man factors (C1) | Lack of experience, knowledge and skills of seafarers (D11) | 145 | 12.9 |
| | Seafarers unstable mental and emotional state (D12) | 31 | 2.8 |
| | Insufficient physical condition of the seafarers (D13) | 78 | 6.9 |
| | Seafarers activities before accident (D14) | 40 | 3.6 |
| Machine factors (C2) | Availability and reliability of equipment to be used for work (D21) | 24 | 2.1 |
| | Maintenance status of equipment to be used for work (D22) | 53 | 4.7 |
| | Level of automation of the equipment to be used for the job (D23) | 21 | 1.9 |
| Media factors (C3) | Seafarers of various nationalities (D31) | 11 | 1.0 |
| | Excessive overtime and insufficient rest time (D32) | 117 | 10.4 |
| | Ship structure, such as work space structure (D33) | 21 | 1.9 |
| | Type and condition of cargo loaded on the ship (D34) | 34 | 3.0 |
| | Working conditions according to ship schedule (D35) | 161 | 14.3 |
| Management factors (C4) | Insufficient company safety management and management policy (D41) | 54 | 4.8 |
| | Insufficient supervision of work management of companies and ships (D42) | 90 | 8.0 |
| | No on-board training and drills for seafarers (D43) | 67 | 6.0 |
| | Procedures and work instructions that do not reflect the latest regulations (D44) | 117 | 10.4 |
| | Absence of tank cleaning work plan on ship (D45) | 61 | 5.4 |

The questionnaire results can be summarized as follows. The analysis of the 17 detailed 4M causes shows that the response ratio for the working conditions according to the ship schedule (D35) was the highest at 14.3%. This was followed by a lack of experience, knowledge, and skills of seafarers (D11) at 12.9%, the procedures and work instructions that do not reflect the latest regulations (D44), and excessive overtime and insufficient rest time (D32) at 10.4%. The response ratio for seafarers of various nationalities (D31) was the lowest, at 1.0%, among the 17 causes, and the response ratios for the level of equipment automation (D23) and the ship structure, such as work space structure (D33), were low at 1.9%. Among the 4M factors, the response ratio for management factors (C4) was the highest at 34.6%, followed by media factors (C3) at 30.6%, human factors (C1) at 26.1%, and machine factors (C2) at 8.7%. It was generally observed that the respondents regarded management factors as the most important causes of the unsafe tank atmosphere environment (B1), and they placed a higher importance on media factors than on human and machine factors.

### *3.2. Fault Tree Analysis (FTA) Results*

Because tertiary factors can be the cause of secondary factors, the probability of secondary factors was determined by applying a logical sum OR gate to the probability of the tertiary loads.

Using the survey results in Table 2, the probabilities of the tertiary factors are shown in Table 4.

**Table 4.** Probabilities of 4M categories.

| 4M Categories | Probability (%) |
|---|---|
| Man factors (C1) | 23.97% |
| Machine factors (C2) | 8.48% |
| Media factors (C3) | 27.65% |
| Management factors (C4) | 30.20% |

The 4M factors in descending order of the probability of occurrence of secondary factors are: management factors > media factors > man factors > machine factors. It can be observed that the underlying causes of the unsafe tank atmosphere environment appear higher in management factors or media factors than in human factors.

This is somewhat different from previous studies that verified the hypothesis that most marine accidents are caused by human error, such as human lack of situational awareness [7–9]. In other words, it differs from previous studies in that more measures for management and media factors than the human factor are required for accident prevention.

Because the 4M secondary factors can also be causes of primary factors, the probability of occurrence of an unsafe tank atmosphere environment by the primary factor, which is the underlying cause, can be obtained by applying a logical sum OR gate to the probability of the secondary factors, as shown in Table 5.

**Table 5.** Probabilities of primary cause.

| Primary Cause | Probability (%) |
|---|---|
| Unsafe tank atmosphere environment | 64.86% |

As shown in Table 5, the unsafe tank atmosphere environment exhibited a 64.86% probability of occurrence. Thus, it can be considered to be a major cause of fire and explosion accidents in tankers.

## 4. Discussion

The probability of the occurrence of an unsafe tank atmosphere environment owing to underlying causes is 64.86%. The secondary factors in descending order according to their probability of occurrence are as follows: management factors > media factors > man factors > machine factors. Table 6 compares the probabilities of the occurrence of tanker explosion accidents, owing to an unsafe tank atmosphere environment, between the previous study and the marine accident survey report on accidents that occurred in South Korea.

**Table 6.** Probabilities of primary cause.

| Uğurlu [3] | Marine Accident Survey Report | This Study |
|---|---|---|
| 55.00% | 55.6% | 64.86% |

As shown in Table 6, five out of nine tanker accidents over the last five years (approximately 55.6%), for which the cause of occurrence was identified through accident reports, were caused by unsafe tank atmosphere environments, such as combustibles and oil vapor [3]. Uğurlu's study also used FTA to identify that 55% of all fire and explosion accidents were caused by combustible liquid and gas. Thus, previous studies and the analysis results of the marine accident survey reports are in good agreement.

However, the chain of underlying causes presented in this study for the unsafe tank atmosphere environment leading to fire and explosion accidents in tankers cannot be ignored. Identifying a primary cause probability of 64.86% can be recognized as a sufficiently good research achievement. Moreover, the subfactors of the underlying causes of unsafe tank atmosphere environments are also composed of logical sums. Thus, the larger the number of subfactors and the higher the probability of occurrence, the higher the total probability of the occurrence of underlying causes. However, because this study is limited to an unsafe tank atmosphere environment, future research is required to compare the results with those of various root causes.

As a result of using FTA technique in this study, the probability of the occurrence of underlying causes must be decreased to reduce the probability of the occurrence of unsafe tank atmosphere environments, which is the primary cause. According to the chain, this will then decrease the occurrence rate of fire and explosion accidents in tankers.

Furthermore, the occurrence of unsafe tank atmosphere environments is more affected by management and media factors than human factors; therefore, countermeasures against these issues are also required.

Education and training for seafarers are important, but selective prevention measures through other approaches, such as ship management and the working conditions of the seafarers, are also required. The following methods are proposed:

First, if the procedures and work guidelines are fully complied with and the company and ships are better managed and supervised than at present, management factors can be reduced by approximately 14.9%, from 30.20% to 15.32%. The probability of the occurrence of an unsafe tank atmosphere environment can thereby be reduced by approximately 7.5%, from 64.86% to 57.37%.

Second, if sufficient working and resting times can be guaranteed for working seafarers by adjusting the ship schedule, media factors can be reduced by approximately 21.89%, from 27.65% to 5.76%. The probability of the occurrence of an unsafe tank atmosphere environment can thereby be reduced by approximately 10.63%, from 64.86% to 54.23%.

Finally, if the experience, knowledge, and skills of seafarers—particularly senior officers who conduct risk assessments and provide approvals for work—are improved via proper training and education through investments by ship owners, human factors can be reduced by approximately 11.25% from 23.97% to 12.72%. The probability of unsafe tank atmosphere environments arising can thereby be reduced by approximately 5.2% from 64.86% to 59.66%. Additionally, management, supervision, and improvement efforts should be targeted not only toward seafarers but also managers to solve these problems.

This study only examined the underlying causes of unsafe tank atmosphere environments in tankers; however, response measures to all marine accidents through various major factors should be determined in the future. Furthermore, the secondary probability of occurrence was determined through an expert survey; therefore, if the probability data is collected through continued research, the reliability of the research will be further enhanced. In addition, the survey is limited on several counts. First, the survey on the expert group was conducted only in South Korea; if such a survey can be conducted in various countries, the study results would be more generalized. Second, although the content validity of the questionnaire items was evaluated by the experts, validity evaluation using the correlation coefficient was not performed. Therefore, further research on these aspects is required in the future. Such research will greatly contribute to the prevention of fire- and explosion-related accidents in tankers, and to the preparation and enhancement of measures for safety management to prevent such accidents.

## 5. Conclusions and Suggestions for Further Research

To reduce the frequent occurrence of marine fire and explosion accidents, the primary causes and underlying causes of these accidents were investigated, and their probabilities of occurrence were analyzed using FTA. In addition, response measures to reduce fire and explosion accidents were proposed based on the analysis results.

In this study, the IMO Resolution and the 4M disaster analysis method were combined, and an expert survey was conducted based on this combination. From these results, the probability with which the underlying causes lead to primary causes was investigated. The results of this study can be summarized as follows:

First, many prior studies have focused on unsafe tank atmosphere environments as the biggest cause of fire and explosion accidents in tankers.

Second, previous studies typically identify human factors as the biggest cause of other marine accidents, such as collisions and groundings, and they focus on response measures to reduce the occurrence of marine accidents owing to human factors. However, in this study, the probability of the occurrence of fire and explosion accidents owing to management factors was 30.20%, and that owing to media factors was 27.65%. This is higher than the 23.87% probability of occurrence owing to human factors. Therefore, management and media factors are considered to be greater causes of fire and explosion accidents in tankers. Hence, preparing response measures to address these factors will be effective.

Third, to prevent unsafe tank atmosphere environments, procedures and work guidelines should be complied with and supervised by the company and ships, and sufficient working time should be guaranteed.

The results of analyzing the underlying causes and probability of occurrence of accidents will reduce fire and explosion accidents in tankers and help protect human life and property in the sea and marine environment. However, this study has some limitations such as the focus on unsafe tank atmosphere environments and calculation methods of occurrence probability which depend only on the expert survey. Furthermore, generalizing the results of this study through follow-up research on various primary and underlying causes of tanker fire and explosion accidents in the future will enable the identification of the characteristics of fire and explosion accidents in tankers, the preparation of preventive measures, and the improvement of the safety management of ships and companies. Moreover, to improve the reliability of this research, an additional study is required on the probability of the occurrence of the underlying causes.

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