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A mission-oriented risk assessment methodology for naval vessel fire caused by non-contact explosions using Bayesian Networks

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Abstract

In order to understand the fire damages on warship caused by non-contact explosion, a mission-oriented risk assessment methodology was developed in this paper. Firstly, an eight-step flow chart was proposed to analyze the fire effect on a warship, and the main factors, which determined the fire consequences, were summarized. Then based on the specialist marking methods and statistical data, the fire damage on warship could be calculated by using Bayesian Networks, which is a nice tool to assess the risk for complicated system. Finally, the methodology was applied a hypothetical ship with five compartments. The results show that fire intensity mainly depends on the fuel load and the fire damage depends on the function occupancy rate. Moreover, the result of sensitivity analysis indicates that fire damage could be effectively reduced by some ways, such as decrease leakage caused by shock, shorten the response time of fire detection and so on.

Keywords: Mission-oriented; Fire risk assessment; Bayesian networks; Naval vessel; Non-contact explosions

1. Introduction

In wartime naval vessels would be hit by contact explosion and non-contact explosion. Although non-contact explosion does not directly hit naval vessel, it can cause fire by shock wave. As one of the most serious disasters, the ship fire attracts many attentions.

As to commercial ship, International Maritime Organization (IMO) approved a structured and systematic methodology for assessing risk which was named Formal Safety Assessment (FSA) [1]. This method was initially used in IMO rule-making process, and then for ship fire risk assessment [2]. FSA provides a relatively standard assessment process which focuses on fire frequency reduction, but it is not intended to cover risk control options for consequence reduction.

However, warship emphasizes govern severity of a fire rather than probability of accidental ignition [3] and FSA is not proper for warship. Table 1 shows some fire risk assessment methods focusing on fire severity reduction for naval vessels. A Ship Fire Safety Engineering Method (SFSEM) was developed from Engineering Method for Building Fire Safety by U.S. Coast Guard Research and Development Center. SFSEM is a probabilistic-based structured and comprehensive fire risk analysis methodology which treats all types of surface ships as a fire safety system [4]. All relevant aspects of fire safety are considered, including the growth and spread of fire, the effectiveness of passive and active fire protection measures [5]. Moreover, NKF Engineering Associates developed a Fire Loading and Self-inflicted Fire Risk Analysis for a U.S. Navy Destroyer design. This method aimed at achieving a balanced ship design with respect to fire hazards, compartment value and fire protection [6]. The method was then improved by Materials Research laboratory of Australia, and the assessment results were demonstrated in an easily understood set of colored charts [3].

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Although two above methods focused on fire consequence (severity) rather than fire frequency (probability), the attentions were still paid on fires caused by self-inflicting in peacetime rather than by weapon attacks in wartime. In wartime, due to non-contact explosion attack, the fire ignition probability would greatly increase, the occurrences of fuel spills and hull crack would change combustion circumstance, and the damage of suppression system would reduce its efficiency. Compared to the condition in peace time, the wartime state would be more severe.

The purpose of this paper is to develop a Mission-oriented Risk Assessment methodology for naval vessel fire caused by Non-contact Explosions (MRANE). Firstly, an eight-step flow chart was given to introduce the evolution of fire and its effect on the ship. Secondly, the influence factors were figured out, and an index system was constructed in a hierarchy structure. Then based on Bayesian Networks, the fire damage on the warship could be calculated, and this method was used to study a case in the end.

Table 1. Application areas of different fire risk assessment methods

Fire cause	Methods focusing on fire frequency/probability reduction (merchant ship)	Methods focusing on fire consequence/severity reduction (naval vessel)
Internal cause (self-inflicting)	FSA	SFSEM/ Self-inflicted Fire Risk Analysis
External cause (weapon attacks)	—	MRANE (present work)

2. Methodology of risk assessment

2.1. Assessment flow

For naval vessels, the fire risk caused by non-contact explosion can be analyzed as following the flow chart shown in Fig. 1.

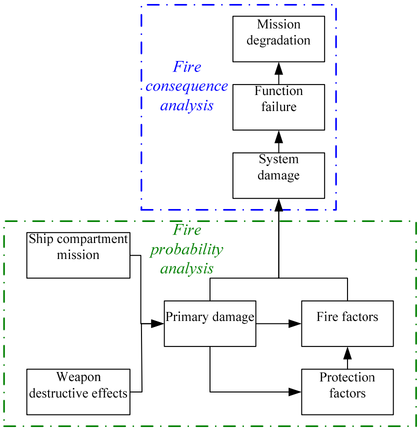

Fig. 1. Flow chart of MRANE.

Step 1: Ship compartment mission analysis

Assessment Goal:

The fire risk assessment goal is quite different for warship and merchant ships. For naval vessels, the goal of fire risk assessment is to evaluate the ship's residual ability to continue the assigned military mission after a fire caused by weapon attacks. So it can be called a mission-oriented assessment method. Among all of missions of naval vessels, the most important one is combat mission, which is concentrated in this paper.

Assessment scope:

Compartment is the basic unit of a ship. In this paper we tried to develop a method to assess the degradation of a compartment ability to perform combat mission after a fire caused by shock of non-contact explosions. Then the fire risk of each compartment in a ship could be evaluated, and the total fire risk of the ship could be obtained.

Assessment levels:

The function of compartment depends on the systems in the compartment. Thus, the assessment could be divided into three levels, *i.e.* mission level, function level and system level. As shown in Fig. 2, mission level is supported by function level which mainly includes fighting, moving and floating. The weight of each function varies with change of the mission. Function level is supported by system level which mainly includes fighting system, electric system, moving system and floating system.

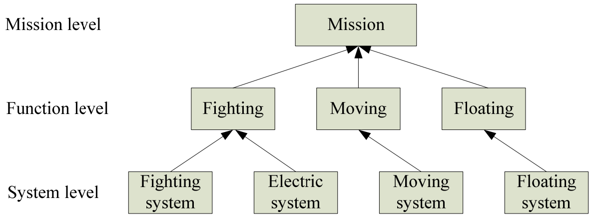

Fig. 2. Assessment levels.

Step 2: Weapon destructive effects analysis

In general, if the class and mission of a warship were known, the type of weapon which would attack the ship is determined. Then the hit probability and destructive can be obtained. This paper concentrates on non-contact explosions, thus primary damages are mainly caused by shock waves, and fire and flooding could induce secondary damages. In this paper, we just care about the fire risk.

Step 3: Primary damage analysis

In this paper the ship survivability is considered after a given shock loading and the shock damages on system functions:

- Hull cracks
- System damages, such as failure of suppression systems and degradation of fighting systems
- Electric short circuit
- Pipeline break

Step 4: Fire factors analysis

Fire factors include ignition, fuel load and ventilation condition. The ignition may be caused by failure of system or weapon attacks, and the system failure could be ignored because of its low probability in wartime. So in this paper just the ignition by shock accident is considered. Fuel load includes the original fuel in the compartment and the fuel leakages from broken pipelines. Usually, it can be considered that the fire duration might to be proportional to the fuel load and fire intensity is proportional to the ventilation.

Step 5: Protection factors analysis

As in FSA, active and passive fire protection measures are needed to control and extinguish fire. Active fire protection measures mainly include fire detection (auto and manual), fire suppression (auto and manual), firefighting training and management, shut down the ventilation and so on. Passive fire protection factors include the use of fire insulation on bulkheads and decks, fire tight cabling and piping bulkhead penetrations, and fire dampers in ventilation ducts. However, it should be noted that protection measures would fall failure partly or entirely under weapon shocks[7].

Step 6: System damage analysis

The main changes for the fire caused by the shock wave can be concluded as follows:

- The probability of ignition greatly increases
- Fuel leaks from broken pipelines
- Hull cracks change ventilation condition
- Efficiency of firefighting system decrease

Step 7: Function failure analysis

Once the system damages have been evaluated, the function failure can be determined.

Step 8: Mission degradation analysis

Finally, if we take account of all these function failures, the mission degradation of the compartment can be achieved.

2.2. Construction of index system

Based on the above analysis, an index system of MRANE is constructed, as shown in Fig. 3. The index system is a set of related factors referred in the assessment flow, and is arranged in hierarchical structure. The top of this index system is ship mission, which depends on function factors, hazard factors and protection factors. Each of these three factors also includes some sub-factors. Finally, a factors tree is produced, and it can clearly illustrate the relationship among these factors.

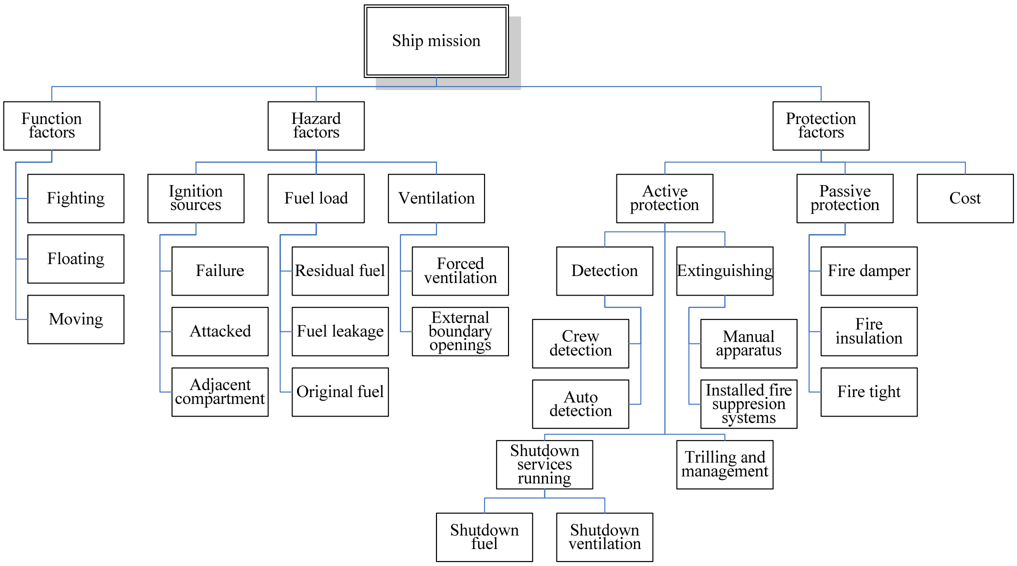

Fig. 3. Index system of MRANE.

2.3. Modeling by Bayesian network

Basic theory of Bayesian networks

Compared to the traditional risk assessment techniques, e.g. fault tree and event tree, Bayesian Networks (BN) can express complex net system and is a better analysis of a dependable system [8]. The use of BN modeling risk assessment had been suggested by Japan in 2006 [9], and was formally adapted in FSA by IMO in 2007 [10]. As a powerful modeling tool, BN has been successfully used to evaluate ship risk in many aspects, including grounding, collision and fire [9, 11-13].

BN is a causal network that enables a graphical representation of causal relations between different parameters. It can be expressed as following:

$$BN = << V, E >, P > \tag{1}$$

V denotes a set of nodes, which can represent random variables. Each variable has a number of states.

E denotes a set of directed links, which denotes the causal relationship among the nodes. For example, a directed link $E = <V_i \rightarrow V_j>$ denotes that node V_i has an effect on node V_j. So node V_i is called the parent of node V_j, and node V_j is called the child of V_i. The node without parents is called root node.

$<V, E>$ can identify a qualitative part of a risk model, while P can present its quantitative part. P describes how the states of a node depend on the parents of the node, *i.e.* a conditional probability table (abbreviated CPT).

Fire risk assessment model for compartment

In order to build a fire risk assessment model for naval vessels shocked by non-contact explosions, some limitations and hypotheses are given:

- The ship is shocked by non-contact explosion when performing a combat mission.
- The ignition is caused by weapon attack.
- The functions supporting mission only include fighting and moving, while flooding is ignored.
- The effect of electric failure on fighting system and moving system is not considered.
- The activity of crew is not considered.
- The cost of fire protection is not considered.
- Compartments of the ship are considered independent, and no fire spread from compartment to compartment. So the passive protection system is assumed 100% effective.

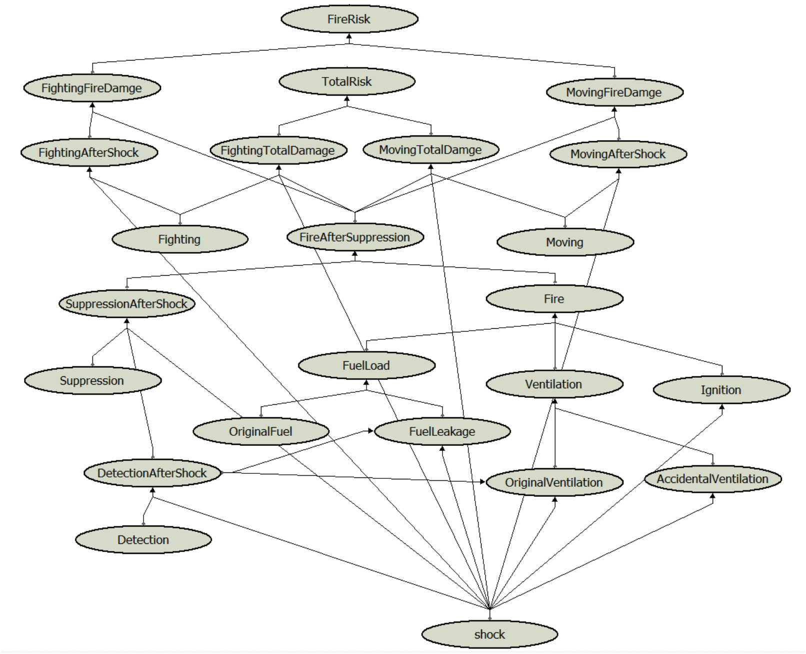

Fig. 4. BN model of MRANE.

Then the BN model of MRANE can be constructed following the steps bellow.

Firstly, the nodes of the model should be determined. According to the eight-step analysis and the index system constructed above, a number of fire risk parameters have been achieved, as shown in Fig. 3. Based on the hypotheses above, some parameters can be ignored. Finally, 24 parameters are selected and each parameter is treated as a node (V_i) of BN model. All the nodes are listed in Table 2.

Secondly, the relationship among the nodes should be determined. Based on the eight-step analysis as well as the assumptions above, the relationship among the nodes are determined as Fig. 4.

Finally, the probability distribution of each node should be determined. Each node of the BN model is a binary-state random variable, *i.e.* YES or NO. The YES state affirms the occurrence of the event or operational status of the system represented by the node and NO indicates the opposite state. The definition of the YES state of each node can be seen in Table 2. The probability of a node in one state can be obtained in two ways, *i.e.* statistics and experts.

3. Case study and analysis

3.1. Case description

Figure 5 shows a hypothetical frigate class ship with 5 compartments, which is represented by C1, C2, C3, C4 and C5. The subdivision of fighting system, moving system, fuel loading and other main input data are given in Table 3.

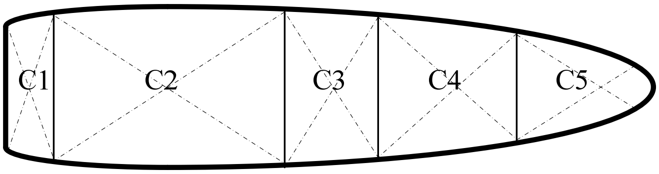

Fig. 5. Compartment subdivision of a hypothetical frigate class ship.

Table 2. Nodes description of MRANE

No.	Name of node V_i	Definition of the YES state of V_i	Parent Node(s)
1	*Shock*	Ship is hit by non-contact explosion.	—
2	*Original Fuel*	The fuel load in a compartment before attack can sustain a fire which can destroy the whole compartment.	—
3	*Fighting*	The whole fighting system is in the compartment.	—
4	*Moving*	The whole moving system is in the compartment.	—
5	*Detection*	The fire can be detected as soon as it occurs.	—
6	*Suppression*	The suppression system can extinguish the fire in a compartment before shock.	—
7	*Detection After Shock*	After shock the detection system can detect fire as soon as fire occurs.	*Shock*, *Detection*
8	*Suppression After Shock*	The suppression system can extinguish the fire in a compartment after shock.	*Shock*, *Suppression*, *Detection After Shock*
9	*Fuel Leakage*	The fuel load of leakage can sustain a fire which can destroy the whole compartment.	*Shock*, *Detection After Shock*
10	*Fuel Load*	The sum of *Original Fuel* and *Fuel Leakage*.	*Original Fuel*, *Fuel Leakage*
11	*Original Ventilation*	The machinery ventilation can supply sufficient oxygen.	*Shock*, *Detection After Shock*
12	*Accidental Ventilation*	Ventilation caused by hull cracks can supply sufficient oxygen.	*Shock*
13	*Ventilation*	The sun of *Original Ventilation* and *Accidental Ventilation.*	*Original Ventilation*, *Accidental Ventilation*
14	*Ignition*	There is an ignition in the compartment.	*Shock*
15	*Fire*	There is a fire which can destroy the whole compartment.	*Fuel Load*, *Ventilation*, *Ignition*
16	*Fire After Suppression*	There is a fire which can destroy the whole compartment after suppression.	*Suppression After Shock*, *Fire*
17	*Fighting Total Damage*	The fighting function is lost caused by shock and fire.	*Fighting*, *Fire After Suppression*, *Shock*
18	*Moving Total Damage*	The moving function is lost caused by shock and fire.	*Moving*, *Fire After Suppression*, *Shock*
19	*Total Risk*	The sum of *Fighting Total Damage* and *Moving Total Damage.*	*Fighting Total Damage*, *Moving Total Damage*
20	*Fighting After Shock*	The fighting system still works after shock.	*Fighting*, *Shock*
21	*Moving After Shock*	The moving system still works after shock.	*Moving*, *Shock*
22	*Fighting Fire Damage*	The fighting function is lost caused by fire.	*Fighting After Shock*, *Fire After Suppression*
23	*Moving Fire Damage*	The moving function is lost caused by fire.	*Moving After Shock*, *Fire After Suppression*
24	*Fire Risk*	The sum of *Fighting Fire Damage* and *Moving Fire Damage.*	*Fighting Fire Damage*, *Moving Fire Damage*

3.2. Results and discussion

Applying the BN model built above to this case, the assessment results can be achieved in probabilistic forms. Fig. 6 (a) presents the fire probability of each compartment, which means how intense the fire will be. It can be seen that the fire probability can be ranked from high to low as C2, C5, C4, C3, C1, whether before or after suppression. It is mainly because of the quantity of fuel load in each compartment.

Table 3. Main input data of a hypothetical frigate class ship

Compartment No.	C1	C2	C3	C4	C5
$P\{Fighting\text{=YES}\}$	0	0.3	0.2	0.4	0.1
$P\{Moving\text{=YES}\}$	0	0.6	0	0.4	0
$P\{Original\ Fuel\text{=YES}\}$	0.1	0.6	0.2	0.3	0.4
$P\{Shock\text{=YES}\}$	0.6	0.6	0.6	0.6	0.6

Figure 6 (b) presents the fire risk (fire consequence) and total risk of each compartment. It ranks C2, C4, C3, C5, and C1 from high to low. This result disagrees with the fire intensity in Fig. 6 (a). This probably because that the compartment fire risk is not only impacted by fire intensity but also by the occupancy rate of fighting and moving in the compartment. For example, although its fire probability is 14.48, the fire risk of compartment C1 is zero, because there is no fighting or moving system in it. Moreover, from Fig. 6 (b), it can be concluded that total risk (the sum of shock damage and fire damage) is higher than fire risk (just fire damage) in a compartment, because total risk includes both fire and shock damage.

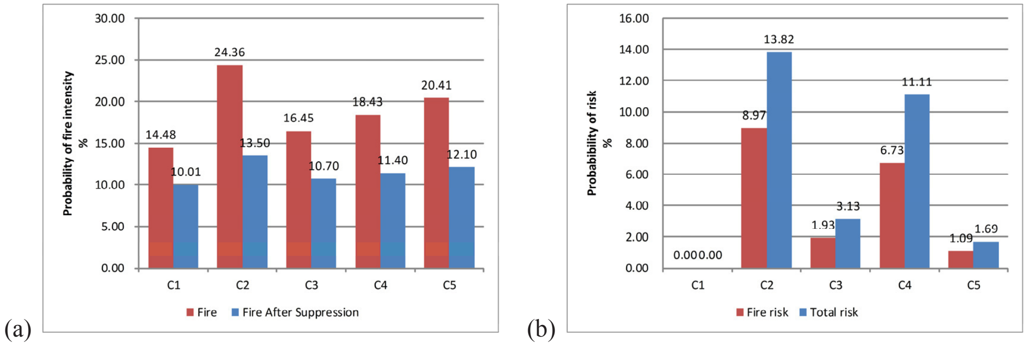

Fig. 6. (a) The probability of nodes fire and fire after suppression. (b) the probability of nodes fire risk and total risk.

This paper focuses on how to reduce fire risk rather than shock damage. In order to reduce fire risk, it is necessary to analyze the sensitivity of fire risk. The sensitivity analysis equation is expressed as:

$$S_{FireRisk}=\left|\frac{P(FireRisk\,|V=\text{YES})-P(FireRisk\,|V=\text{NO})}{P(V=\text{YES})-P(V=\text{NO})}\right| \tag{2}$$

where $S_{Fire\ Risk}$ is the sensitivity degree of node *Fire Risk*, V is the node which influences *Fire Risk*. V can be the node as *Detection*, *Detection After Shock*, *Suppression*, *Suppression After Shock*, *Fuel Leakage*, *Ventilation* and *Ignition*. “YES” and “NO” are the states of V.

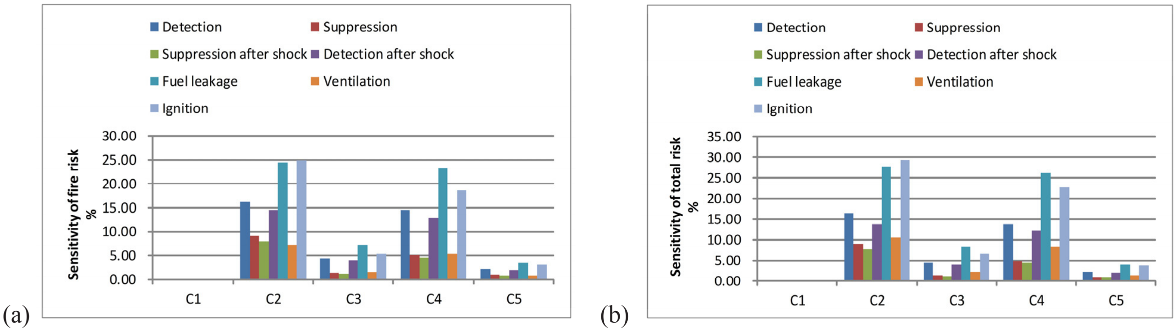

Fig. 7. Sensitivity analysis of (a) fire risk. (b) total risk.

Figure 7 (a) presents the result of fire risk sensitivity analysis in each compartment. It is found that *Fire Risk* is highly influenced by *Fuel Leakage* and *Ignition*, moderately by *Detection* and *Detection After shock* and little by *Suppression*, *Suppression After Shock*, *Ventilation*. Furthermore, the result of total risk sensitivity analysis in each compartment basically corresponds with Fig. 7 (a).

According to Fig. 7 (a) and Fig. 7 (b), both fire risk and total risk can be reduced effectively:

- Decrease fuel leakages by enhancing shock resistance of pipelines.
- Decrease occurrence of electric arc, spark caused by shock.
- Shorten the detection response time and improve the survivability of detection system after shock.

4. Conclusions

When a naval vessel is attacked by non-contact explosion, the fire scenario would be great different from ship fire in peace time. Thus, a mission-oriented fire risk assessment methodology for naval vessel shocked by non-contact explosions (MRANE) was developed in this paper.

The key points of MRANE were three parts:

- An eight-step flow chart
- An index system in a hierarchy structure
- A BN model.

The flow chart is a mission-oriented assessment procedure, which makes it more standard and more systematic to evaluate fire risk of naval vessels. It can be applied to naval vessels not only under combat mission but also under other missions. The index system presents the effect factors of warship fire, which should be noticed in fire protection design. The BN model is a quantitative risk assessment model, which can simulate complex problems, such as ship fires, more precisely.

The MRANE can be applied to naval vessel designs, and the assessment results can show clearly which compartment is overprotected and which is lack of protection. Thus, an optimized design can be achieved by balancing fire protection factors and other influence factors among compartments. Because MRANE is a mission-oriented method, finally it can promote the ship ability to continue combat mission in the circumstance of fire caused by non-contact explosions.

Acknowledgements

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