Nuclear Engineering and Technology 54 (2022) 4560–4570

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Safety analysis of marine nuclear reactor in severe accident with dynamic fault trees based on cut sequence method

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ARTICLE INFO

Article history:
Received 22 December 2021
Received in revised form
2 August 2022
Accepted 14 August 2022
Available online 12 September 2022

Keywords:
Safety analysis
Marine nuclear reactor
Dynamic fault tree
Cut sequence
Extended cut sequence
Severe accident

ABSTRACT

Dynamic fault tree (DFT) and its related research methods have received extensive attention in safety analysis and reliability engineering. DFT can perform reliability modelling for systems with sequential correlation, resource sharing, and cold and hot spare parts. A technical modelling method of DFT is proposed for modelling ship collision accidents and loss-of-coolant accidents (LOCAs). Qualitative and quantitative analyses of DFT were carried out using the cutting sequence (CS)/extended cutting sequence (ECS) method. The results show nine types of dynamic fault failure modes in ship collision accidents, describing the fault propagation process of a dynamic system and reflect the dynamic changes of the entire accident system. The probability of a ship collision accident is 2.378×10^{-9} by using CS. This failure mode cannot be expressed by a combination of basic events within the same event frame after an LOCA occurs in a marine nuclear reactor because the system contains warm spare parts. Therefore, the probability of losing reactor control was calculated as 8.125×10^{-6} using the ECS. Compared with CS, ECS is more efficient considering expression and processing capabilities, and has a significant advantage considering cost.

1. Introduction

Since the beginning of the 21st century, the world has faced two of the most challenging issues: climate change [1] and the energy dilemma [2]. In the context of global climate change, there is an urgent need to reduce greenhouse gas emissions, and the “zero-emission” feature of marine nuclear power devices [3] meets this requirement. In addition, nuclear power is also an effective means to deal with the energy crisis; therefore, the development of marine nuclear power has practical significance.

The nuclear power industry is a high-risk industry. For policy-makers and citizens, environmental and public safety are the most important issues [4]. The Chernobyl nuclear accident in the former Soviet Union [5], Three Mile Island nuclear accident in the United States [6], and Fukushima nuclear accident in Japan [7] have propagated global public concern considering nuclear safety. Due to the complexity of each system of marine nuclear reactor, it is necessary to analyze the safety of marine traffic accidents for marine nuclear reactor to ensure the safe operation of ships in the ocean; the reactor accident fault analysis of marine nuclear reactor is an important part of safety analysis.

Zheng et al. [8] summarized the research methods and calculation tools of dynamic probabilistic risk assessment(DPRA), and analyzed the application of DPRA method in nuclear reactors. Among them, the analysis method of DFT is one of DPRA. DFT and its related research methods have received extensive attention in safety analysis and reliability engineering [9–13], with the ability of dynamic system modelling and the capability of conducting reliability modelling for characteristics such as dynamics, dependence, non-monotony, polymorphism, and randomness. Hsueh [14] proposed a modelling method for the dynamic probabilistic risk assessment of nuclear power plants based on an accident dynamic simulator, which uses a discrete dynamic event tree as the main accident scene model for analyzing the dynamic probabilistic safety of a steam generator tube rupture event in an NPP. Zheng et al. [8] proposed a method of applying multi-fidelity simulation to DPRA. The high fidelity data are used for adaptive training, and the simulation results are predicted by the low fidelity model. The results show that the multi-fidelity method is effective for DPRA and greatly reduces the computational cost. Karanki [15] conducted a

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https://doi.org/10.1016/j.net.2022.08.014
1738-5733/

DFT analysis of a medium-break LOCA in a pressurized water reactor (PWR) to study the influence of break size, number of high-pressure safety injection sequences, and interaction between the time and rate of primary cooling and secondary depressurization on the success of the accident sequence. Alfonsi [16] used a newly developed reactor analysis and virtual control environment DFT function to analyze a dynamic random system, and used DFT to evaluate the dynamic probabilistic safety of a PWR under power failure. Karanki [17] used the method of DFT quantization to study and analyze the LOCA in the reactor, and compared the results of the classical event tree model estimation to solve the dynamic problems of the system dependence and continuous random variable characteristics of NPP. The impact of improved dynamic modelling on risk estimation is proposed. To calculate the influence of dynamic scenarios and random variables on risk assessment, Karanki [18] applied DFT to examine the accident scenario space more comprehensively. DFT replaced the event tree model, quantified the core damage frequency, and revealed the accident sequence under different description conditions. Amirsoltani [19] calculated the core damage frequency of the VVER-1000 /V446 nuclear reactor plant station blackout accident based on DFT. The results showed that the DFT method could provide relevant risk factors and effective suggestions for worker recovery actions.

Until now, conceptualization and design have paid less attention to risk assessment and modelling, with little research on the safe operation of complex systems [20]. Many studies have shown that research on the safety of autonomous marine has great challenges. Parhizkar et al. analyzed the influence of complex systems considering dynamic factors and feedback loops and made great progress in the application of complex technology and methods to the dynamic behaviour of complex systems [21–27]. Thieme et al. [28] conducted a risk assessment of structural collisions, ship collisions, and foundation risks on marine autonomous surface ships. These risk assessments cannot be directly applied to practice without considering control algorithms, software, and human-computer interactions. Therefore, Parhizkar et al. studied the probability and dynamic behavior in the process of complex system risk assessment [29,30].

Online probabilistic risk assessment of complex marine system [20] summarizes some dynamic probabilistic risk assessment [31] methods. The dynamic event sequence diagram/dynamic event tree method comprehensively considers many types of dynamic factors such as the sequence of events, dependent rules, constraints, and hierarchical identification. The Markov chain method is mainly used to describe complex systems that cannot be modelled by closed-loop solutions and reliability block diagrams and to represent the correlation and probability of the system state changing with time. The DFT method extends the event logic gate of the static fault tree (SFT) to consider the dynamic behavior of the system over time. The dynamic Bayesian network method simulates the change in variables of the Bayesian network with time and then updates the results. The aforementioned research on dynamic probabilistic risk assessment methods mainly focuses on the analysis of time variation and complex systems and has made significant contributions to applications in the marine, nuclear and aerospace industry. In this study, the probabilistic risk assessment method of DFT is applied. The CS is applied when considering the time series of a complex system, and the ECS is applied when considering the failure of spare parts of a complex system. The main advantage of this method is that the analysis time is reduced significantly.

Qualitative and quantitative analyses of severe reactor accidents have been carried out, but there are few studies on the safety evaluation of marine nuclear power installations after severe accidents. The application of the DFT analysis method to the consequence evaluation of marine nuclear reactor collisions and LOCAs is even less. Therefore, this research is based on the technical modelling of DFT and carries out DFT modelling for ship collision accidents and LOCA and applies the CS/ECS method to qualitatively and quantitatively analyze the DFT. Because electronic components will be damaged during operation and have the characteristics of no memory. Therefore, this study does not use the calculation tools of DPRA such as MCDET [32], ADAPT [33], ADS-IDAC [34] and TRETA [35], but assumes that the lifetime of all components of the DFT meets the exponential distribution, and then carried out qualitative analysis and quantitative solution of the DFT. This study has the characteristics of fast reliability modeling, which can effectively guide the optimization design of the accident system structure, improve the expression and processing capabilities of dynamic logic, and significantly reduce the solution cost.

In section 2, the basic types of ship accidents are described and the DFT models of the ship collision accident and the LOCA in a marine nuclear reactor are established respectively. In section 3 and 4, the qualitative and quantitative analysis of DFTs for ship collision accident and LOCA are conducted, respectively. Section 5 summarizes the research work and draws a conclusion. A subsection roadmap of the sections 2, 3 and 4 is shown in Fig. 1 below:

2. Ship accident and its DFT modelling

Section 2.1 describes the internal and external accidents under consideration on the ship. Section 2.2 overviews the logical symbol for the DFT. Technical modelling of DFT for ship collision accident and subsequent LOCA are described in Sections 2.3 and 2.4, respectively.

2.1. Ship accident

Marine nuclear reactor is a general term of reactor system that provides propulsion power and other required energy (such as electricity, steam, hot water, compressed air, and compressed liquid) for ships. Taking the marine nuclear reactor as the research object, this study carried out a safety analysis of the marine nuclear reactor after a severe accident, including the modelling method of the combination of SFT and DFT, and carried out a qualitative and quantitative analysis of the accident. The weak link of the marine nuclear power unit is analyzed, and effective measures and useful suggestions for the improvement of the marine nuclear reactor are proposed.

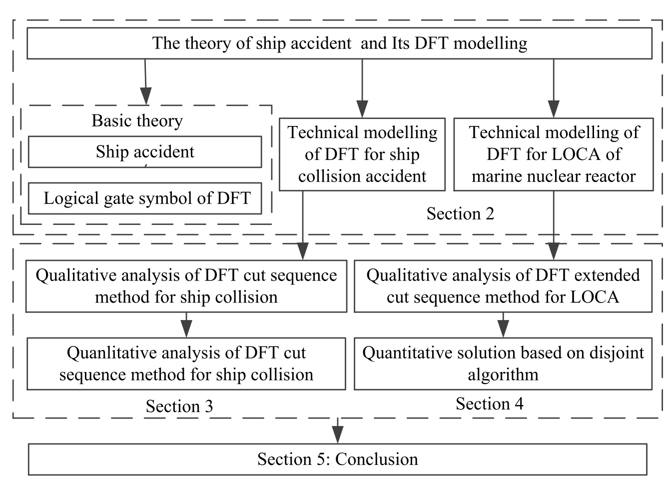

Fig. 1. A subsection roadmap of the sections 2, 3 and 4.

When the marine nuclear reactor sails at sea, external accidents of the ship are mainly caused by factors such as collision, striking a reef, contact damage, fire disaster/explosion, grounding, self-sinking, and wind disasters. Internal nuclear reactor accidents of ships mainly include LOCA, steam turbine shutdown accidents, ship power failure accidents, rod ejection accidents, and other severe accidents. Among the internal and external accidents of ships, collisions and LOCAs have the highest probability and significant influence. Therefore, the fault tree modelling of extremely severe ship accidents is first carried out, followed by the fault tree analysis of ship collision and LOCA. However, considering the dynamic relationship between the time sequence of mechanical device failure and human factors, DFT modelling was carried out, and the DFT analysis method was applied for qualitative and quantitative analysis, which makes the safety analysis of ship severe accidents more accurate and provides deeper theoretical and accurate data support for effective nuclear emergency decision-making.

2.2. Logical gate symbol of DFT

DFT refers to a fault tree that contains at least one dynamic logic gate. It extends the application scope of the traditional fault tree analysis method to dynamic systems and can model the reliability of systems with the characteristics of sequence correlation, resource sharing, and cold-and hot-spare parts. In addition, because the DFT contains the SFT, the basic method of the traditional SFT is also used in the analysis.

The priority AND (PAND) gate is an extension of the AND gate. It adds conditions based on the AND gate, which specifies the order of occurrence of input events. For a PAND gate with one output event and two input events, an output event occurs if and only if both input events A and B occur and event A occurs before event B is satisfied. A graphic symbol of the PAND gate is shown in Fig. 2 (a).

Cold spare parts (CSP) refer to spare parts that do not fail before work is activated. Such a system cannot be modelled by the SFT because such a failure mode cannot be expressed in the same event frame with a combination of basic events. A CSP gate has one basic input and several optional inputs, and all the input events are basic. When all the input events occur, the output events of the CSP gate occur. Graphical symbols of the CSP gate are shown in Fig. 2 (b).

The warm spare parts (WSP) gate had an initial input and several alternative inputs. The initial input refers to the components that are working when the system starts working, and the substitute input is used as a warm reserve. The substitute input is in the warm reserve state before the failure of the working parts, and the failure rate of the input parts is α times that of the normal operation, $0 \leq \alpha \leq 1$, and they are replaced one by one after the failure of the working components. The WSP gate has an output event. The output event occurs only after all the input events (initial input and substitute input) occur. A graphic symbol of the WSP gate is shown in Fig. 2 (c). The hot spare part (HSP) gate is a special case of the WSP gate, and the hot reserve state corresponds to the warm reserve state when $\alpha = 1$. The CSP gate can be used as a special case of the WSP gate, that is, in the cold reserve state, $\alpha = 0$.

The WSP has two states: active and dormant. Analyzing the two input WSP gates without shared spare parts, if the loses efficacy of spare parts in the active state is recorded as S_a and the failure in the dormant state is recorded as S_d, then a spare part is either in the active state or in the dormant state. As the failure rate of the WSP changes from a dormant state to an active state, there are different failure probability distributions of spare parts in the dormant and active states, and S_a and S_d are different events.

2.3. Technical modelling of DFT for ship collision accident

In this study, reliability modelling of DFT was carried out for ship collision accidents and LOCAs of nuclear reactors. The DFT includes a static and dynamic fault subtree, and the DFT includes the analysis method of a SFT. Therefore, the SFT processing method forms part of the theoretical basis of the DFT analysis method. Qualitative analysis of a fault tree generally deduces its minimum cut set, which mostly depends on a series of Boolean rules. The key reason is that the fault tree can be described by a logical expression, and the minimum cut set is the result of the simplification of the logical expression of the fault tree.

However, for DFT analysis with dynamic logic gates, this study applies the DFT-CS method and puts forward the algebraic framework of CS method. CS refers to the sequential failure relationship in which the top events in the DFT depend on the basic events. Based on the time sequence rules derived from Boolean rules, algebraic description modelling of DFT and qualitative analysis of DFT were carried out. The fault tree of a severe accident on a ship is shown in Fig. 3.

The water environment of a certain jurisdiction in China is 224.5 km in length. To identify the risk causes of ship collisions in this water area, and analyze and evaluate each risk cause, the data of 24 ship collision accidents and dangerous situations in this jurisdiction for a certain year were analyzed. Taking ship collision as the top event, the collision caused by operational negligence, physical and environmental factors, and violation operation as the direct cause of events, we analyze their direct cause events level by level until the basic events that cannot be further divided, and build a dynamic fault tree, as shown in Fig. 3.

According to the above DFT, the 24 ship collision accidents and dangerous situations in the jurisdiction are analyzed individually to obtain the number of relevant accidents for each risk factor (basic events), as shown in Table 1. The collisions caused by other ship collisions (such as ship equipment failure) that do not appear in the data of the research object are not analyzed and discussed here.

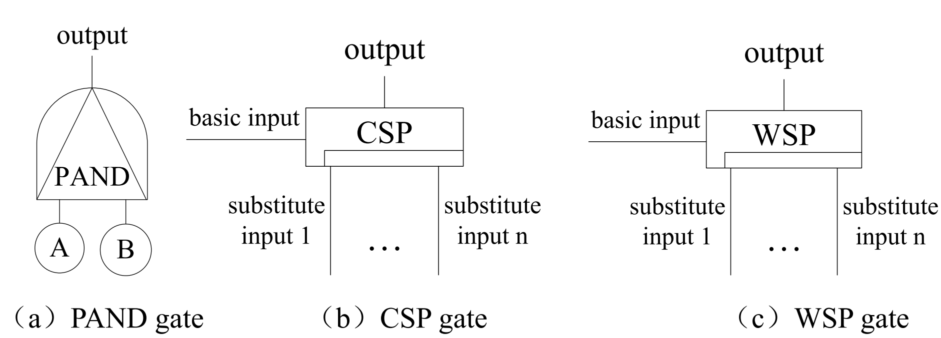

Fig. 2. Logic gate symbol of DFT.

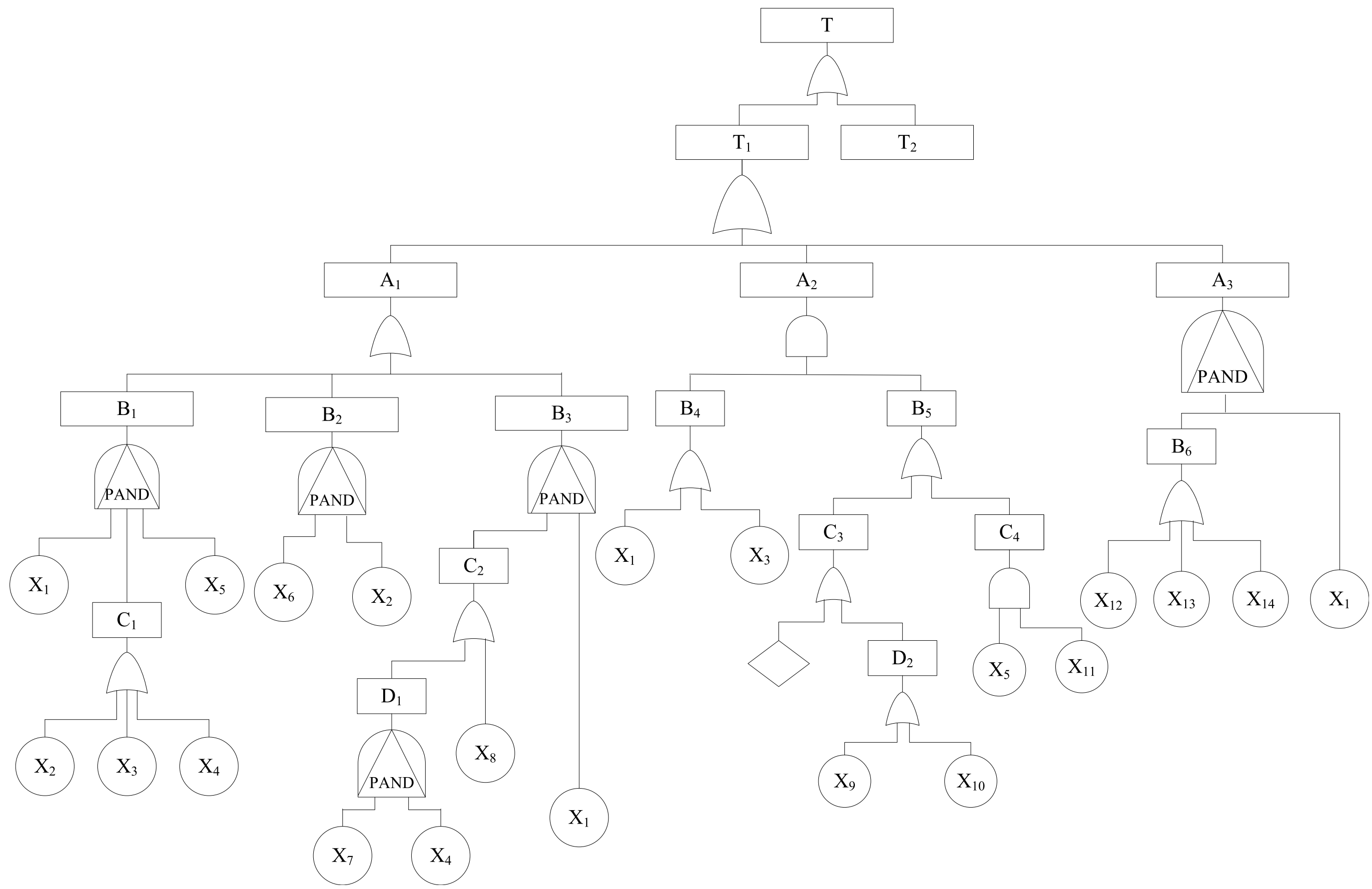

Fig. 3. The DFT of a severe accident on the ship.

Table 1
Letter symbols of ship collision accident and their corresponding events.

Serial number	Events	Serial number	Events(Number of basic incidents)
T_1	Ship collision	D_2	Poor visibility
A_1	Collision caused by operational negligence	X_1	Unguarded navigation (9)
A_2	Collision caused by physical and environmental factors	X_2	Rudder control error (5)
A_3	Collision caused by violation operation	X_3	Neglect to wait and see (5)
B_1	Navigational fault	X_4	Misjudgment of ship position during top towing (5)
B_2	Will make mistake	X_5	Improper emergency operation (20)
B_3	The ship deviated from the course	X_6	Will make the intentions inconsistent (3)
B_4	Remedy deficiency	X_7	Improper avoidance of the third ship (2)
B_5	Objective factors	X_8	Violation of traffic separation (5)
B_6	Urgent situation caused by violation operation	X_9	Foggy (3)
C_1	Operating negligence	X_{10}	Poor visibility on the morning and evening (1)
C_2	Active yaw	X_{11}	Top towed broken cable (1)
C_3	Environmental defects	X_{12}	Adventure overtaking (1)
C_4	The ship is out of control	X_{13}	Fatigue driving (2)
D_1	Simultaneous avoidance	X_{14}	Violation of other regulations (4)

2.4. Technical modelling of DFT for LOCA of marine nuclear reactor

When a marine nuclear reactor has an LOCA, it only considers whether the system can achieve emergency shutdown and does not consider accident treatment after the reactor shutdown. If the reactor can realize shutdown within the allowable time, the reactor is considered safe; otherwise, it is out-of-control. If an LOCA occurs in the reactor system during operation, the water-charging system doubles as a high-pressure injection system, and the accident response system sends a signal to start the corresponding controller to start water injection into the reactor. Taking the out-of-control reactor as the top event, four direct cause events were analyzed: failure of the water charging system, failure of the accident response system, failure of manual shutdown when the operator finds various faults, and inability of the operator to normally judge the break position and isolate it in time. In this study, the DFT is constructed from the failure of water make-up system with warm spare parts, and the DFT reliability model of water make-up system failure is established. Fig. 4 shows the fault tree of the out-of-control reactor after LOCA of the marine nuclear reactor.

The water-charging system of the reactor also serves as a high-pressure injection system, and its working process is divided into a

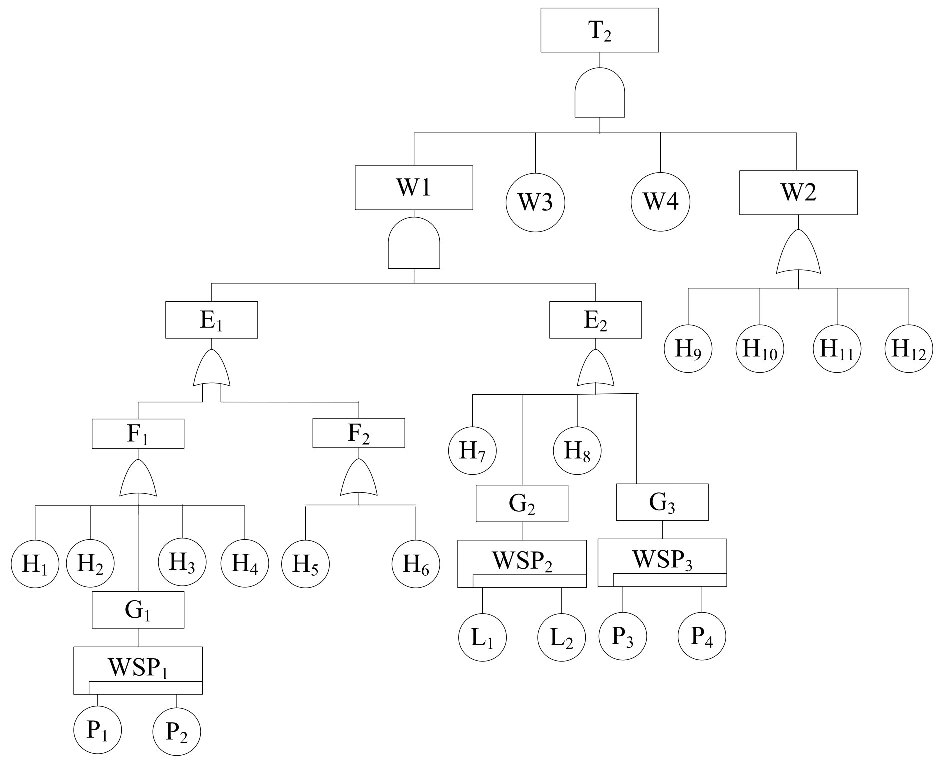

Fig. 4. The DFT of the out-of-control reactor after occurring LOCA of marine nuclear reactor.

water-supply preparation stage and a water-supply filling stage. The water-supply preparation stage comprises these parts: a deaerator, two control valves, two make-up water pumps, a heat exchanger, and an upper distillation tank. The water-supply filling stage includes two filters, two ion exchangers, and two upper charging pumps. E_1 in Fig. 4 represents the water-supply preparation stage, which consists of two parallel devices F_1 and F_2. F_1 and F_2 both indicate the failure water supply preparation subsystem. In the water supply preparation subsystems, at least one subsystem needs to fail. In each water supply preparation subsystem, at least one instrument or equipment needs to fail. E_2 indicates the water-supply filling stage. The water-charging system becomes invalid only when the water-supply preparation stage and the filling stage fail simultaneously. A schematic of the water-charging system is shown in Fig. 5. A pressure sensor was used to monitor reactor pressure. The system activates the pressure controller when the pressure reaches the minimum limit and activates the reactor shutdown logic through the pressure controller. A water-level sensor was used to monitor the water level of the pressurizer. The system starts the level controller when the water level reaches the low limit, and the system starts the shutdown logic through the water level controller.

It was assumed that the probability of success of the water source in the water-charging system was 1. It is believed that the water source did not break down during the mission. Through the analysis of the water replenishment system and the response of each part to the accident after the LOCA of a marine nuclear reactor, the DFT of the water replenishment system failure and the SFT of the system response are established, as shown in Fig. 4. Table 2 lists the corresponding top, intermediate and basic events in Fig. 4.

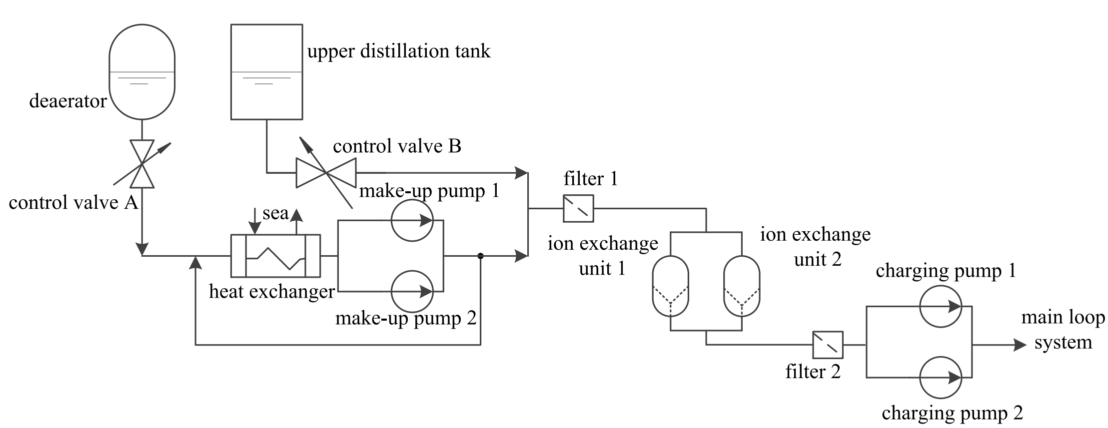

Fig. 5. The schematic diagram of water charging system.

Table 2
Letter symbols of LOCA and their corresponding events.

Serial number	Events	Serial number	Events
T_2	Out-of-control reactor after LOCA	H_4	Failure of upper distillation tank
W_1	Failure of water make-up system	H_5	Failure of control valve B
W_2	All kinds of sensors or controllers are faulty and the operator fails to find them in time	H_6	Failure of filter 1
W_3	Operator found various faults but manual shutdown failed	H_7	Failure of filter 2
W_4	The operator cannot judge the location of the breach and isolate it in time	G_2	Failure of ion exchanger
E_1	Failure of water supply preparation system	L_1	Failure of ion exchanger 1
E_2	Failure of water supply filling system	L_2	Failure of ion exchanger 2
F_1	Failure of water supply preparation subsystem 1	G_3	Failure of charging pump
F_2	Failure of water supply preparation subsystem 2	P_3	Failure of charging pump 1
H_1	Failure of deaerator	P_4	Failure of charging pump 2
H_2	Failure of control valve A	H_8	Pressure sensor failed and the operator failed to detect it in time
G_1	Failure of make-up pump	H_9	Pressure controller failed and the operator failed to detect it in time
P_1	Failure of make-up pump 1	H_{10}	Water level sensor failed and the operator failed to detect it in time
P_2	Failure of make-up pump 2	H_{11}	Water level controller failed and the operator failed to detect it in time
H_3	Failure of heat exchanger		

3. Fault tree analysis of ship collision accident

The qualitative and quantitative analysis of the ship collision accident using DFT cut sequence method are discussed in detail in Section 3.1 and 3.2, respectively.

3.1. Qualitative analysis of DFT cut sequence method for ship collision

A_2 represents the collision caused by the object and environmental factors, and belongs to the static fault subtree. The Boolean algebraic form of the SFT is expressed as:

$$A_2 = B_4 \times B_5 = (X_1 + X_3) \times (C_3 + C_4) = (X_1 + X_3) \cdot (D_2 + X_5 \cdot X_{11}) = (X_1 + X_3) \cdot (X_9 + X_{10} + X_5 \cdot X_{11}) = X_1 \cdot X_9 + X_1 \cdot X_{10} + X_1 \cdot X_5 \cdot X_{11} + X_3 \cdot X_9 + X_3 \cdot X_{10} + X_3 \cdot X_5 \cdot X_{11}$$

Therefore, the minimum cut set corresponding to the A_2 event is obtained: $\{X_1,X_9\}$, $\{X_1,X_{10}\}$, $\{X_1,X_5,X_{11}\}$, $\{X_3,X_9\}$, $\{X_3,X_{10}\}$, $\{X_3,X_5,X_{11}\}$.

After all logic gates of the DFT are transformed into algebraic descriptions, the algebraic description model of the entire dynamic fault tree is obtained, which is called the structural function of the DFT. It is necessary to transform the structural function of DFT into a cut sequence set. Owing to the existence of redundant and contradictory items, it is necessary to convert the form of the cut sequence set into its minimum form. To simplify the process, some extended properties and theorems have been proposed.

For the algebraic description of the PAND gate, suppose that the input of the PAND gate is from left to right, and the output is marked as O_{PAND}. Using the symbol priority relationship, the algebraic description is $O_{PAND} = A_1 \prec A_2 \prec \cdots \prec A_{n-1} \prec A_n$.In the ship collision in the DFT given in Fig. 3, only the PAND gate exists. A_1 represents the collision caused by operational negligence and A_3 represents the collision caused by the violation operation. A_1 and A_3 belong to the dynamic fault subtree. The Boolean description form of the DFT is as follows:

$$A_1 = B_1 + B_2 + B_3 = X_1 \prec (X_2 + X_3 + X_4) \prec X_5 + X_6 \prec X_2 + (\times (X_7 \prec X_4) + X_8) \prec X_1$$

In the algebraic description of the above formula, the corresponding temporal rules derived from Boolean rules and temporal rules generated by temporal logic are applied to eliminate the six contradictory item: $X_2 \prec X_1 \prec X_4 \prec X_5$, $X_3 \prec X_1 \prec X_4 \prec X_5$, $X_3 \prec X_1 \prec X_2 \prec X_5$,

$$X_2 \prec X_1 \prec X_3 \prec X_5,\ X_4 \prec X_1 \prec X_2 \prec X_5,\ X_4 \prec X_1 \prec X_3 \prec X_5$$

The cut sequence set of DFT for collision caused by operational negligence is obtained:

$$A_1 = X_1 \prec X_2 \prec X_5 + X_1 \prec X_3 \prec X_5 + X_1 \prec X_4 \prec X_5 + X_6 \prec X_2 + X_7 \prec X_4 \prec X_1 + X_8 \prec X_1$$

The minimum cut sequence set is obtained using the theorem of the sub cut sequence (denoted as A_{1_MCSS}):

$$A_{1\_MCSS} = X_1 \prec X_2 \prec X_5 + X_1 \prec X_3 \prec X_5 + X_1 \prec X_4 \prec X_5 + X_6 \prec X_2 + X_7 \prec X_4 \prec X_1 + X_8 \prec X_1$$

Using the corresponding temporal rules derived from Boolean rules and the temporal rules generated by temporal logic, the cut sequence set of the DFT caused by the violation operation is obtained as follows:

$$A_3 = B_6 \prec X_1 = (X_{12} + X_{13} + X_{14}) \prec X_1 = X_{12} \prec X_1 + X_{13} \prec X_1 + X_{14} \prec X_1$$

The minimum cut sequence set is obtained using the theorem of the sub cut sequence (denoted as A_{3_MCSS}):

$$A_{3\_MCSS} = X_{12} \prec X_1 + X_{13} \prec X_1 + X_{14} \prec X_1$$

A ship collision accident consists of two dynamic-fault subtrees and one static-fault subtree. Therefore, the algebraic description of the fault tree of a ship collision accident is given by the following equation, and the minimum cut sequence set and minimum cut set of ship collision accidents are expressed as follows:

$$T_1 = A_{1_{MCSS}} + A_{3_{MCSS}} + A_2 = X_1 \prec X_2 \prec X_5 + X_1 \prec X_3 \prec X_5 + X_1 \prec X_4 \prec X_5 +$$

$$X_6 \prec X_2 + X_7 \prec X_4 \prec X_1 + X_8 \prec X_1 + X_{12} \prec X_1 + X_{13} \prec X_1 + X_{14} \prec X_1 +$$

$$(X_1 \cdot X_9 + X_1 \cdot X_{10} + X_1 \cdot X_5 \cdot X_{11} + X_3 \cdot X_9 + X_3 \cdot X_{10} + X_3 \cdot X_5 \cdot X_{11})$$

According to the above formula, there are fifteen failure modes of ship collision accidents, among which nine are dynamic failure modes, which are denoted as Failure mode one to nine.

Failure mode 1: Ship collision accidents caused by unguarded navigation (X_1), rudder control error (X_2), and improper emergency operation (X_5) successively.

Failure mode 2: Ship collision accidents caused by unguarded navigation (X_1), neglect to wait and see (X_3), and improper emergency operation (X_5) successively.

Failure mode 3: Ship collision accidents caused by unguarded navigation (X_1), misjudgment of ship position during top towing (X_4), and improper emergency operation (X_5) successively.

Failure mode 4: Ship collision accidents caused by will make the intentions inconsistent (X_6) and rudder control error (X_2) successively.

Failure mode 5: Ship collision accidents caused by improper avoidance of the third ship (X_7), misjudgment of ship position during top towing (X_4), and unguarded navigation (X_1) successively.

Failure mode 6: Ship collision accidents caused by violation of traffic separation (X_8), and unguarded navigation (X_1)successively.

Failure mode 7: Ship collision accidents caused by adventure overtaking (X_{12}), and unguarded navigation (X_1) successively.

Failure mode 8: Ship collision accidents caused by fatigue driving (X_{13}) and unguarded navigation (X_1)successively.

Failure mode 9: Ship collision accidents caused by violation of other regulations (X_{14}) and unguarded navigation (X_1)successively.

There are six types of static failure modes, which means that all basic events occur and are independent of the sequence. Failure modes 1-9 belong to the dynamic fault failure mode, which describes the fault propagation process of the dynamic system, reflects the dynamic change of the entire fault system, and can effectively guide the structural optimization design of the fault system.

3.2. Quanlitative analysis of DFT cut sequence method for ship collision

Because the mechanisms of the impact of accident causes on the system state in dynamic and static system are different, for dynamic reliability analysis, the time sequence of the change in accident causes will also have an impact on the system state. Therefore, the importance analysis method of a static system cannot be directly used, and a new importance calculation method suitable for dynamic system reliability analysis needs to be defined. The probability of the top event of the DFT in the form of a minimum cut sequence set was calculated to evaluate the unreliability of the system and obtain other reliability parameters. The DFT of a ship collision accident is analyzed, and the minimum cut sequence set has only priority failure logic. Therefore, the probability of the top event of the DFT was calculated and analyzed quantitatively. Fourteen types of basic events lead to ship collisions. The unreliability function $F(S)$ for each type of basic event is obtained as follows:

$$F(S) = \frac{N_i}{S} \tag{1}$$

where, N_i represents the number of ship collision accidents caused by basic event X_i, and S represents the ship flow in the water area in a certain year. In a certain year, the average flow of ships in the area was 609 ships per day, with a total of 222285 ships throughout the year.

Failure probability is also called the failure probability density or loses efficacy probability density. Therefore, the failure probability density function $f(S)$ is the reciprocal of the unreliability function:

$$f(S) = \frac{dF(S)}{dS} \tag{2}$$

$$\Pr = \{X_1 \prec X_2 \prec X_5\}(S) = \int_{S}^{+\infty}\int_{S_5}^{+\infty}\int_{S_2}^{+\infty} N_5 \cdot \left(-\frac{2}{S_5^2}\right) \cdot N_2 \cdot \left(-\frac{2}{S_2^2}\right) \cdot N_1 \cdot \left(-\frac{2}{S_1^2}\right) dS_1 dS_2 dS_5$$

Simplified by $\Pr = \{X_1 \prec X_2 \prec X_5\}(S) = \frac{1}{3} \cdot \frac{N_1 \cdot N_2 \cdot N_5}{S^3}$. Hence, according to Equations (1) and (2), the number of basic events of ship collision and the probability calculation formula of the minimum CS, the probability of ship collision accident is 2.378×10^{-9}.

4. Fault tree analysis of LOCA of marine nuclear reactor

The qualitative analysis of LOCA in a marine nuclear reactor using DFT cut sequence method is discussed in detail in Section 4.1. In Section 4.2, the extended cut sequence method of DFT is used to quantitatively analyze and solve the LOCA in a marine reactor, and the specific solution is based on the disjoint algorithm.

4.1. Qualitative analysis of DFT cut sequence method for LOCA

According to the fault tree in Fig. 4, the Boolean algebraic structure of the out-of-control reactor in the LOCA of a marine nuclear reactor is as follows:

$$T_2 = W_1 \cdot W_2 \cdot W_3 \cdot W_4$$

Through an analysis of the T_2 fault tree, W_1 represents the failure of the water make-up system. The fault subtree contained both static and dynamic subtrees. Therefore, the cut sequence method was used for both qualitative and quantitative analyses. W_2 represents the fault of various sensors or controllers, which the operator fails to find in time. There is only one static subtree in the fault subtree, which is solved using the traditional fault tree analysis method. W_3 and W_4 are basic events, which are bottom events. Fig. 4 shows the DFT for the failure of the water make-up system. The combination of static and dynamic logic gates constitutes the algebraic description model of DFT, also known as the structural function of DFT. The structural function is the Boolean function representation of the failure relationship between the top event and the basic event of the DFT, which is used for the qualitative and quantitative analyses of the DFT. Therefore, the structural function for the DFT of W_1 water make-up system failure is as follows:

$$W_1 = (H_1 + H_2 + H_3 + H_4 + H_5 + P_1 \prec P_{2a} + P_{2d} \prec P_1) \cdot (H_6 + H_7 + L_1 \prec L_{2a} + L_{2d} \prec L_1 + P_3 \prec P_{3a} + P_{3d} \prec P_3)$$

where P_{2a}, L_{2a}, and P_{3a} indicate that the spare parts fail in the active state and P_{2d}, L_{2d} and P_{3d} indicate that the spare parts fail in the dormant state.

The corresponding temporal rules derived from the Boolean rules and temporal rules generated by temporal logic were applied.

Using the corresponding temporal rules derived from Boolean rules and the temporal rules generated by temporal logic, the structural function is transformed into the minimum cut sequence set. It was found that the minimum number of cut sequences of the failure dynamic fault tree of water make-up system is 114. The minimum number of cut sequences is large, the qualitative analysis is cumbersome, and it is difficult to solve quantitatively using the cut sequence method. Therefore, the extended cut sequence method for a dynamic fault tree was proposed for solution analysis.

4.2. Quanlitative analysis of DFT extended cut sequence method for LOCA

In the cut sequence of the complete DFT, because each cut sequence only represents a basic event combination to determine the failure sequence, the expression ability of the cut sequence is reduced and the operation efficiency is greatly reduced. The scale of the DFT of the water make-up system failure is relatively large, which eventually leads to a surge in the number of cut sequences, and long solution time. Therefore, this study proposes a DFT analysis method for an extended cut sequence set based on the cut sequence method. Based on the disjoint algorithm of the minimum extended cut sequence set of DFT, the disjoint extended cut sequence set is transformed into the standard extended cut sequence set, and conflict detection, time limit set simplification, basic event set sorting, and quantitative calculation are carried out for each cut item of the standard extended cut sequence to obtain the quantitative results of each standard extended cut sequence, and then comprehensively solve the system reliability parameters.

Due to the complex characteristics of the reactor water make-up system, and after a severe accident occurred in the marine nuclear reactor, a large number of radionuclides leaked out of the system device, and the instrument equipment was damaged by a large number of radiation. In this special condition, it is assumed that the failure of water make-up system follows exponential distribution. Failure rate parameters of components according to exponential distribution properties are shown in Table 3. The water make-up preparation system and water make-up filling system without shared spare parts are regarded as independent static subtrees. The analysis of the independent static subtree is relatively simple, and the unreliability of the static subtree at time t can be directly listed as $F_{S1}(t)$ and $F_{S2}(t)$.

$$F_{S1}(t) = 1 - e^{-\lambda_1 t} \cdot e^{-\lambda_2 t} \cdot e^{-\lambda_3 t} \cdot e^{-\lambda_4 t} \cdot e^{-\lambda_5 t},\ F_{S2}(t) = 1 - e^{-\lambda_6 t} \cdot e^{-\lambda_7 t}$$

4.3. Solution based on disjoint algorithm

The minimum extended cut sequence set of the independent dynamic subtree of the water make-up preparation system is $MECS_1 = \{P_1 \cdot P_{2a} ® P_1 < P_{2a}, P_{2d} \cdot P_1 ® P_{2d} < P_1\}$.

In the temporal failure logic model, the extended cut sequence is used to describe the sequence occurrence behavior of events, and the minimum extended cut sequence set of the dynamic fault tree after analysis and discussion is:

$$MECS_1 = \{E ® T\} = \{P_1 \cdot P_{2a} ® P_1 < P_{2a}, P_{2d} \cdot P_1 ® P_{2d} < P_1\}$$

® represents the relationship between the input $\{P_1, P_{2a}, P_{2d}\}$ and the output.

$T = \{t(P_1) < t(P_{2a}), t(P_{2d}) < t(P_1)\}$, the output is generated only when the input $\{P_1, P_{2a}, P_{2d}\}$ is aging under the condition of time limit set T. Assuming that P_1 occurs at time $t(P_1)$, P_{2a} occurs at time $t(P_{2a})$, and so on, where $t(P_1) < t(P_{2a})$, $t(P_{2d}) < t(P_1)$, then output will be generated at the last failure moment above, otherwise no output will be generated. Indeed, the use of DFT can be justified in view of the properties of the system under consideration.

The minimum extended cut sequence set of the independent dynamic subtree of the water make-up filling system is $MECS_2 = \{L_1 \cdot L_{2a} ® L_1 < L_{2a}, L_{2d} \cdot L_1 ® L_{2d} < L_1\}$ and $MECS_3 = \{P_3 \cdot P_{3a} ® P_3 < P_{3a}, P_{3d} \cdot P_3 ® P_{3d} < P_{31}\}$.

The unreliability of the independent dynamic subtree of the water make-up preparation system and water make-up filling system at time t is F_{d1}、 F_{d2} and F_{d3}. Therefore, the unreliability of the entire water make-up system at time t is:

$$F(t) = [1 - (1 - F_{S1}(t)) \cdot (1 - F_{d1}(t))] \cdot [1 - (1 - F_{S2}(t)) \cdot (1 - F_{d2}(t)) \cdot (1 - F_{d3}(t))] \tag{3}$$

(1) Disjoint extended cut sequence set to generate dynamic subtree

P_1, P_{2a} and P_{2d} are represented by x_1, x_2 and x_3 respectively for convenience of expression, so the minimum extended cut sequence set of the independent dynamic subtree of the water make-up preparation system is:

$$MECS_1 = \{x_1 \cdot x_2 ® x_1 < x_2, x_3 \cdot x_1 ® x_3 < x_1\}$$

The minimum extended cut sequence set is transformed into a disjoint extended cut sequence set. According to the disjoint algorithm, the detailed steps are as follows:

Table 3
Failure rate of each component exponential distribution of water make-up system.

Symbol	Component	Basic events	Failure rate($\times 10^{-6}h^{-1}$)
H_1	Deaerator	Failure of deaerator	2
H_2	Control valve A	Failure of control valve A	1
P_1	Make-up pump 1	Failure of make-up pump 1	5
P_{2a}	Make-up pump 2	Make-up pump 2 fails in active state	5
P_{2d}		Make-up pump 2 fails in dormant state	3
H_3	Heat exchanger	Failure of heat exchanger	2
H_4	Upper distillation tank	Failure of upper distillation tank	1
H_5	Control valve B	Failure of control valve B	1
H_6	Filter 1	Failure of filter 1	3
H_7	Filter 2	Failure of filter 2	3
L_1	Ion exchanger 1	Failure of ion exchanger 1	4
L_{2a}	Ion exchanger 1	Ion exchanger 2 fails in active state	4
L_{2d}		Ion exchanger 2 fails in dormant state	2
P_3	Charging pump 1	Failure of charging pump 1	5
P_{3a}	Charging pump 2	Charging pump 2 fails in active state	5
P_{3d}		Charging pump 2 fails in dormant state	3

Table 4
Quantitative comparison of two methods of water make-up preparation system.

Quantitative method	n_1	n_2
MECS	2	2
CSS	2	11

Table 5
Quantitative comparison of two methods of water make-up filling system.

Quantitative method	n_1	n_2
MECS	4	4
CSS	4	22

$$V_1 = \{110\}, S_1 = \{110\}, T_1 = \{x_1 < x_2\}$$

$$V_2 = \{101\}, S_2 = \{111\}, T_2 = \{x_3 < x_1\}$$

$$C \leftarrow E_1 ® T_1 = x_1 x_2 ® x_1 < x_2$$

② Consider V_2 and S_2, where $L_1 = 2$, the decomposition of V_2 with respect to L_1

$$V_2(2) = \{111\}, T_2 = \{x_3 < x_1\},\ \text{delete}$$

$$V_2(-2) = \{1-11\}, T_2 = \{x_3 < x_1\},\ \text{retain}$$

The disjoint extended cut sequence set composed of two extended cut sequences can be obtained by transforming the composite vector left after decomposition into a basic event set and the corresponding time limit set.

(2) Disjoin the extended cut sequence set and its probability solution

$$DECS = C = \{x_1 x_2 ® x_1 < x_2, x_1 \overline{x_2} x_3 ® x_3 < x_1\}$$

$$F_{d1}(t) = \Pr(x_1 x_2 ® x_1 < x_2) + \Pr(x_1 \overline{x_2} x_3 ® x_3 < x_1) = \iint f(t_1) f(t_2) d\Omega_1 + (1 - \Pr(x_2)) \iint f(t_1) f(t_3) d\Omega_2 \tag{4}$$

where, $f(t_n)$ is the failure probability density function of the basic event x_n, integral region, $\Omega_1 = \{t_1 < t_2\}$, and $\Omega_2 = \{t_3 < t_1\}$.The solution methods and steps of $F_{d2}(t)$ and $F_{d3}(t)$ are the same as those above.

The quantitative analysis and comparison results of the dynamic subtree of the make-up preparation system and the make-up filling system using the minimum ECS and the CS set methods are shown in Table 4 and Table 5, respectively. The minimal extended cut sequence (MECS) refers to the probability of solving the minimum extended cut sequence set using the ECS method. The cut sequence set (CSS) refers to solving all the cut sequences of the DFT according to the CS method. n_1 is the number of elements in the minimum extended cut sequence set or cut sequence set. n_2 is the number of elements in the minimum extended cut sequence set after the disjoint method, or the number of elements to be solved in the minimum cut sequence set according to the inclusion-exclusion rule. It can be seen from Tables 4 and 5 that the number of elements in the minimum extended cut sequence set is equal to the number of elements in the minimum cut sequence set; however, the number of elements in the extended cut sequence set after the disjoint method is far less than the number of elements in the minimum cut sequence set to be solved by the inclusion-exclusion rule. The minimum extended cut sequence method is more efficient in terms of expression and processing abilities, and the solution overhead of the MECS method has obvious advantages over the CSS method.

F_{d1} , F_{d2} and F_{d3} represent the failure probabilities of make-up pump, ion exchanger and charging pump, respectively, which can be determined from the probability calculation equation (4) proposed above. Each disjoint extended cut sequence or cut sequence were solved and multiple integrals and approximate solutions were used to obtain the unreliability of the minimum extended cut sequence of the dynamic subtree at different times, as shown in Table 6.

$F(t)$ represents the failure probability of the entire water make-up system, which can be calculated according to the probability calculation formula (3). The unreliability of the entire water make-up system is shown in Table 7.

We assume that the probability of failure of various sensors and the operator's failure to find them in time is 0.05. The probability of simultaneous occurrence of the operator finds various failures but fails to manually shutdown and the operator's failure to judge the position of the break normally and isolate them in time is 0.05. Therefore, the probability of an out-of-control reactor after an LOCA of the ship's nuclear reactor was 8.125×10^{-6}。

5. Conclusion

This study analyzes the causes of collision accidents when ships are sailing at sea and summarizes the fourteen basic events leading to ship collisions. Based on the changes in complex dynamic systems, a safety analysis method for marine nuclear reactors based on the cut sequence method/extended cut sequence method of DFT was proposed. In this method, the time sequence of fault tree events is considered, dynamic fault tree modelling of ship collision

Table 6
Unreliability of dynamic subtree.

Unreliability of dynamic subtree	One year (8760 h)	Two years (17520 h)	There years (26280 h)
F_{d1}	1.449×10^{-3}	5.473×10^{-3}	1.1637×10^{-2}
F_{d2}	8.801×10^{-4}	3.37×10^{-3}	7.266×10^{-3}
F_{d3}	1.449×10^{-3}	5.473×10^{-3}	1.1637×10^{-2}

Table 7
Unreliability of water make-up system.

Unreliability of water make-up system	One year (8760 h)	Two years (17520 h)	There years (26280 h)
$F(t)$	3.25×10^{-3}	3.85×10^{-3}	4.86×10^{-3}

accidents is carried out using the cut sequence method, and the failure mode of the entire accident system is obtained by combining SFT and DFT. Its main advantage is that it reflects the dynamic changes in the entire accident system. The dynamic failure behaviour of basic events in ship collision accidents is described, effectively guiding the structural optimization design of accident systems. Therefore, the probability of a ship collision accident is 2.378×10^{-9}.

The water-charging system of a marine nuclear reactor is complex. There are two ways for the failure of the water-charging system to occur and spare parts in the system. Considering the failure mode of DFT with spare parts, the extended cut sequence method was used for quantitative analysis of DFT. In addition, comparative analysis and research on the cut sequence method and the extended cut sequence method were carried out. The results show that the extended cut sequence method has a higher efficiency in terms of expression ability and processing ability, and has a significant advantage in terms of solution overhead. A more reliable model is obtained using DFT instead of SFT by incorporating warm-spare parts. Qualitative and quantitative analyses are more accurate, providing deeper theoretical support and more accurate data for effective nuclear emergency decision-making.

The quantitative model in this study is also applicable to other non-exponential distribution cases; however, the non-exponential distribution case is much more complex than the exponential distribution case; in many cases, it is not analytically integrable. The existing computer algebra system has many limitations in dealing with such problems and requires more mathematical skills and approximate numerical calculation methods.

Funding

This work was supported by the Postgraduate Scientific Research Innovation Project of Hunan Province [CX20210922].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their sincere information to Zou Shuliang, Xu Shoulong and Wang Junlong for their guidance and help in this paper.

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