**GUIDANCE NOTES**
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CHINA CLASSIFICATION SOCIETY

# Guidelines for Risk Assessment of Hydrogen-Powered Ships

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# BRIEF DESCRIPTION

To adapt to the rapid development of marine applications of hydrogen fuel, China Classification Society (CCS), in conjunction with the research achievements of the national key R&D programme project "Key Technologies for Typical Hydrogen-Powered Ships" and the current state of industry development, has conducted research on the applicability, procedural standardisation, and assessment criteria of risk assessment methods for hydrogen-powered ships, based on the research outcomes of hazard identification and quantitative hydrogen safety assessment for hydrogen-powered ships. This has led to the establishment of a comprehensive risk assessment (qualitative and quantitative) capability for hydrogen-powered ships and the development of the Guidelines for Risk Assessment of Hydrogen-Powered Ships (hereinafter referred to as the Guidelines).

The Guidelines aim to provide a standardised process for the risk assessment of hydrogen-powered ships throughout their entire life-cycle, covering the design, construction, and operation phases. This ensures that risks can be effectively identified and managed at every stage, from design to operation, thereby contributing to enhanced ship safety and reliability.

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# CHAPTER 1 GENERAL

## Section 1 GENERAL PROVISIONS

### 1.1.1 Goal

1.1.1.1 The goal of the Guidelines is to provide a standardized process for the application of risk assessment methods throughout the full life cycle of hydrogen-powered ships, focusing on core risks such as hydrogen leakage, fire and explosion. Through qualitative and quantitative risk assessment, the Guidelines assist the relevant parties in better understanding the risks to which they are exposed, so as to implement more targeted risk control measures.

### 1.1.2 Application

1.1.2.1 The Guidelines set out the process of and related requirements for hazard identification, frequency analysis, consequence analysis and personnel risk analysis, and apply to qualitative and quantitative risk assessment for hydrogen-powered ships.

1.1.2.2 The risk assessment methods referred to in the Guidelines apply to:

（1） the assessment of safety-related design, construction and operation throughout the full life cycle of hydrogen-powered ships;

（2） the risk assessment required in the technical standards[①] for hydrogen-powered ships.

### 1.1.3 Definitions

For the purpose of the Guidelines:

1.1.3.1 A **hydrogen-powered ship** is a vessel that uses hydrogen as fuel or is ready for a hydrogen fuel power system.

1.1.3.2 **Hazard** means a source or a situation that has the potential for causing damage to people, health, property or the environment.

1.1.3.3 **Accident** means an uncontrolled event that may entail the loss of human life, personal injuries, environmental damage or the loss of assets and financial interests.

1.1.3.4 **Hazard identification** is a structured risk assessment method used to systematically identify potential hazards that may exist during a project or operation.

1.1.3.5 **Consequence** means the potential negative impact of a hazardous event, such as casualties, environmental pollution or economic loss.

1.1.3.6 **Likelihood** means the probability of a hazardous event occurring, usually based on historical data, expert judgement or statistical analysis.

1.1.3.7 **Risk** is the combination of the likelihood and the severity of the consequences of a hazard, usually used to describe uncertainty and potential loss.

1.1.3.8 **Initial risk** means the risk without considering any safety measures.

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① Such as CCS Guidelines for Ships using Hydrogen Fuel and Guidelines for Marine Hydrogen Fuel Bunkering Operation. Where referenced documents are not specifically version-dated in the Guidelines, the latest version is applicable.

1.1.3.9 **Residual risk** means the risk remaining after risk treatment.

1.1.3.10 **Risk matrix** is a matrix consisting of the probability of occurrence of all hazards and their corresponding consequences, used to rank hazards.

1.1.3.11 **Process parameter** means the physical and chemical characteristics relating to a process, such as temperature, pressure, flow rate, etc.

1.1.3.12 **Process indicator** means the normal operating conditions of a system or device, i.e., the operational parameters without deviation.

1.1.3.13 **Deviation** means a process parameter deviating from the process target, typically expressed as "guideword + process parameter".

1.1.3.14 **Failure** means the termination of the ability of an item to perform a required function.

1.1.3.15 **Failure mode** means the manner in which a failure of an item is observed.

1.1.3.16 **Failure probability** means the confidence in the occurrence of a failure, measured from 0 to 1. An event with a probability of 0 means that the failure is believed to be impossible to occur; an event with a probability of 1 means that the failure is believed to be certain to occur.

1.1.3.17 **Failure severity** means the severity of the effect of a failure mode on the operation of an item, the environment and the operator; the severity of the effect of a failure mode is related to the system boundary defined in the analysis.

1.1.3.18 **Reliability** means the ability of an item to perform a required function under given conditions and for a given period of time. Reliability = 1 − failure probability.

1.1.3.19 An **initiating event** means the first of a series of events that can result in a hazardous situation or accident.

1.1.3.20 A **failure** means an event that leads to stay of execution of the functionality required in a part or portion of the system, e.g. leakage.

1.1.3.21 A **failure scenario** means a complete set of environments used to define a specified failure event. A scenario is usually followed by a series of subsequent events, i.e. a failure scenario is also a set of failure events. The failure scenario can be equated to the failure events when only one scenario is considered in a simple risk analysis.

1.1.3.22 **Frequency** means the number of times an event occurs per unit time (usually per year).

1.1.3.23 **Probability** is the confidence in the occurrence of an event measured from 0 to 1. An event with a probability of 0 means that the event is unlikely to occur, and an event with a probability of 1 means that the event is certain to occur.

1.1.3.24 **Failure frequency** means the frequency with which failure events occur per year.

1.1.3.25 **Failure consequence** means the result of a failure event which has one or more results.

1.1.3.26 **Individual risk (IR)** is the frequency with which an individual may be harmed to some extent by risk factors in a hazardous area, usually expressed as the frequency of individual deaths per year.

1.1.3.27 **Societal risk (SR)** is the probability that a group of persons (including employees and the public) may be harmed to some extent in a hazardous area, usually expressed as the cumulative accident frequency that N or more persons will become a fatality each year, which is shown in a curve of accumulation frequency, and usually expressed by the curve of the cumulative frequency against the number of deaths (an F-N curve).

# CHAPTER 2 RISK ASSESSMENT APPROACHES AND PROCESS

## Section 1 GENERAL PROVISIONS

### 2.1.1 General Requirements

2.1.1.1 Risk assessment is the overall process of risk analysis and risk evaluation. Risk analysis may be qualitative or quantitative. The specific method adopted for the risk assessment of hydrogen-powered ships is to be determined by considering the analysis objectives and the analysis subject.

2.1.1.2 Qualitative risk analysis determines likelihood and consequences using a fully qualitative method. Applicable methods for hydrogen-powered ships include, but are not limited to, Hazard Identification (HAZID), Hazard and Operability Study (HAZOP), Failure Mode and Effects Analysis (FMEA), etc.

2.1.1.3 Quantitative Risk Analysis (QRA) requires mathematical estimation of probabilities and consequences. It is applicable for quantifying the risk of events with a relatively low probability of occurrence but significant impact, such as leakage, fire, and explosion.

## Section 2 QUALITATIVE RISK ASSESSMENT IMPLEMENTATION PROCESS AND REQUIREMENTS

### 2.2.1 General Requirements

2.2.1.1 The appropriate qualitative risk assessment method is to be selected based on the analysis objectives. For hydrogen-powered ships, during the design stage, HAZID analysis may be used to identify hazards in the design schemes of all shipboard hydrogen-related spaces. HAZOP analysis may be used to identify hazards in the process flow diagrams of the hydrogen fuel storage and supply system and the bunkering system. FMEA may be used to identify hazards in the power plant and systems, including hydrogen fuel engines and fuel cells. During the operation stage, HAZID and HAZOP methods may be used for hazard identification of fuel bunkering operations and special navigation scenarios (e.g., passing through locks or tunnels).

2.2.1.2 The implementation of a qualitative risk assessment includes the preparation phase, the analysis phase, and the reporting phase. The workflow is shown in Figure 2.2.1.2 of this chapter.

### 2.2.2 Implementation process

2.2.2.1 During the preparation phase, the scope of the hazard identification exercise is to be defined, relevant drawings and documents are to be collected, an analysis team is to be formed, and a working meeting is to be planned.

2.2.2.2 The scope of the analysis depends on a number of factors, including:

(1) the physical boundaries of the object of analysis;

(2) the available design description and its level of detail;

(3) any analysis previously undertaken for the system;

(4) the requirements of applicable codes, regulations and relevant standards.

2.2.2.3 The following factors are to be taken into account in determining the objectives of analysis:

(1) the intended use of the analysis results;

(2) the stage of the ship life cycle at which the analysis is carried out;

(3) persons or ship structures that may be at risk;

(4) the requirements of the standards applicable to the ship, including both system safety and operational performance.

2.2.2.4 According to the defined scope of hazard identification and the issues requiring particular attention, the relevant information and documents are to be collected, and historical accident information of previous or similar projects is to be collected as far as possible.

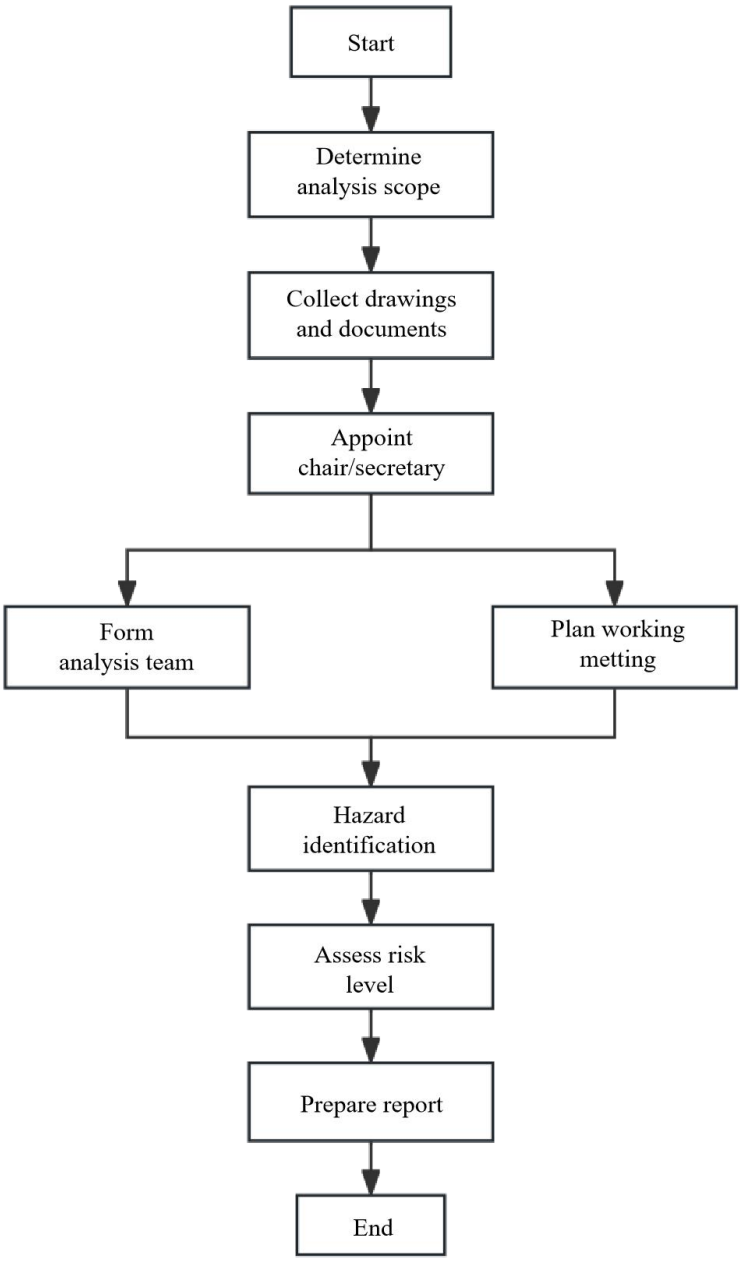



**Figure 2.2.1.2 Qualitative Risk Assessment Implementation Process**

2.2.2.5 The analysis stage includes hazard identification and assessment of risk ranking.

2.2.2.6 Experts from relevant disciplines are to be organised to attend the hazard identification meeting, where hazards are to be identified systematically, all potential hazards are to be determined, and the causes of accidents and possible consequences are to be identified. In this process, the chairman guides the expert team members to carry out "brainstorming" analysis in accordance with the predetermined guidewords, and the recorder takes records. The knowledge, expertise and experience of the analysis team are critical to ensuring the credibility and depth of the analysis results.

2.2.2.7 For HAZID analysis, refer to Chapter 3 of the Guidelines; for HAZOP analysis, refer to Chapter 4 of the Guidelines; for FMEA, refer to Chapter 5 of the Guidelines.

2.2.2.8 Assessment of risk ranking means grading the identified hazards and ranking the hazards, so that the major hazards can be further screened and risk control options proposed in subsequent steps.

2.2.2.9 The risk matrix is the most commonly used and typical method for hazard ranking. In the risk matrix, the risk value is calculated by multiplying the accident frequency by the accident consequence. By taking the logarithm of both sides of the calculation formula, the risk index is obtained as the sum of the frequency index and the severity index:

$$\text{Risk} = \text{Frequency} \times \text{Consequence}$$

$$\log(\text{Risk}) = \log(\text{Frequency}) + \log(\text{Consequence})$$

$$\text{Risk Index (RI)} = \text{Frequency Index (FI)} + \text{Severity Index (SI)}$$

2.2.2.10 The risk matrix is divided into three zones: the high risk zone (H — dark gray zone), the low risk zone (L — white zone), and the transition zone between the two (M — light gray zone). For hazardous events in the high risk zone, risk mitigation measures are to be proposed, and the risk assessment procedure is to be applied again to the proposed measures to assess the residual risk, so as to ultimately reduce the risk to an acceptable level under effective prevention or protection; For hazardous events in the transition zone, whether risk mitigation measures are to be taken is to be decided according to expert judgement and the affordability of the enterprise (e.g. cost, effort and time); For hazardous events in the low risk zone, no additional measures are usually required.

2.2.2.11 In specific applications, the accident frequency, accident consequence and risk ranking may be defined according to the relevant standards② or the owner's requirements. For the definitions and values of frequency and consequence, reference may be made to Table 2.2.2.11(1) and Table 2.2.2.11(2) of this chapter, and for the risk matrix, reference may be made to Table 2.2.2.11(3) of this chapter.

**Frequency Ranking** **Table 2.2.2.11(1)**

| FI | Frequency (/year) | Definition |
|---|---|---|
| 5 | $10^{-1}$ | Most likely — occurs frequently |
| 4 | $10^{-2}$ | Possible — has a good chance of occurring several times during the product life cycle |
| 3 | $10^{-3}$ | Conceivable — might occur at some time during the product life cycle |
| 2 | $10^{-4}$ | Remote — unlikely to occur but possible |
| 1 | $10^{-5}$ | Inconceivable — failure highly unlikely |

**Consequence Severity Ranking** **Table 2.2.2.11(2)**

| SI | Severity | Definitions |
|---|---|---|
| 4 | Catastrophic | The consequences of the accident may lead to catastrophic casualties, property losses and environmental damage, extending beyond the controllable area; the consequences are unacceptable |
| 3 | Severe | The consequences of the accident may lead to severe casualties, property losses and environmental damage, not extending beyond the controllable area, but the consequences are unacceptable |
| 2 | Moderate | The consequences of the accident may lead to personal injury, certain property losses or environmental damage with limited extent of impact; corresponding control measures are to be taken with due consideration of cost-effectiveness |
| 1 | Minor | Such consequence may be negligible |

② Refer to CCS Guidelines for Application of Formal Safety Assessment to Ships, Guidelines for Quantitative Risk Assessment for Oil and Gas and Guidelines for Application of Failure Mode and Effects Analysis (FMEA), IACS Recommendation on Risk Assessment Required by the IGF Code (Rec.146), etc.

**Risk Ranking** **Table 2.2.2.11(3)**

| | FI | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| SI | | A Inconceivable | B Remote | C Conceivable | D Possible | E Most likely |
| 4 | Catastrophic | 5 | 6 | 7 | 8 | 9 |
| 3 | Severe | 4 | 5 | 6 | 7 | 8 |
| 2 | Moderate | 3 | 4 | 5 | 6 | 7 |
| 1 | Minor | 2 | 3 | 4 | 5 | 6 |

2.2.2.12 The qualitative risk assessment report is to contain at least the following:

（1） Cover: including project name, preparation organization, preparation date, etc.;

（2） Contents: listing the sections and page numbers of the report;

（3） Main text, including at least:

① Terms and abbreviations: explanation of professional terms and abbreviations used in the report (if applicable);

② Project overview: brief introduction to the purpose, background and basis of the report;

③ Analysis procedure: introduction to the methods, tools and process used in the hazard identification analysis;

④ Scope of analysis for hazard identification: definition of the object and objectives, the list of technical documentation, and the breakdown into analysis nodes and indenture levels;

⑤ Definition of guidewords/deviations/failure modes;

⑥ Risk acceptability criteria: definition of the risk matrix adopted;

⑦ Conclusions and recommendations: summary of the results of statistical risk analysis, and proposed improvement measures and recommendations.

（4） Appendices, including at least:

① List of drawings, specifications, etc. used in the analysis;

② Meeting attendance sheet;

③ Analysis worksheets, see Appendix 1 of the Guidelines.

# Section 3 QUANTITATIVE RISK ASSESSMENT IMPLEMENTATION PROCESS AND REQUIREMENTS

### 2.3.1 General Requirements

2.3.1.1 Quantitative risk assessment of hydrogen-powered ships is a systematic approach to quantitatively presenting the frequency and consequence of accidents occurring in the ship itself or during operations. In the analysis process, in addition to qualitative analysis of the causes, course, consequences and existing safety measures of accidents, quantitative analysis of the accident frequency and consequence is also to be carried out, and the analysis results are to be compared with the risk acceptability criteria to judge the acceptability of the risk. Where the requirements of the risk acceptability criteria are not met, recommended

measures for risk reduction are to be proposed.

2.3.1.2 The quantitative risk assessment process includes the preparation stage, QRA stage and analysis reporting stage. The work process is shown in Figure 2.3.1.2 below.

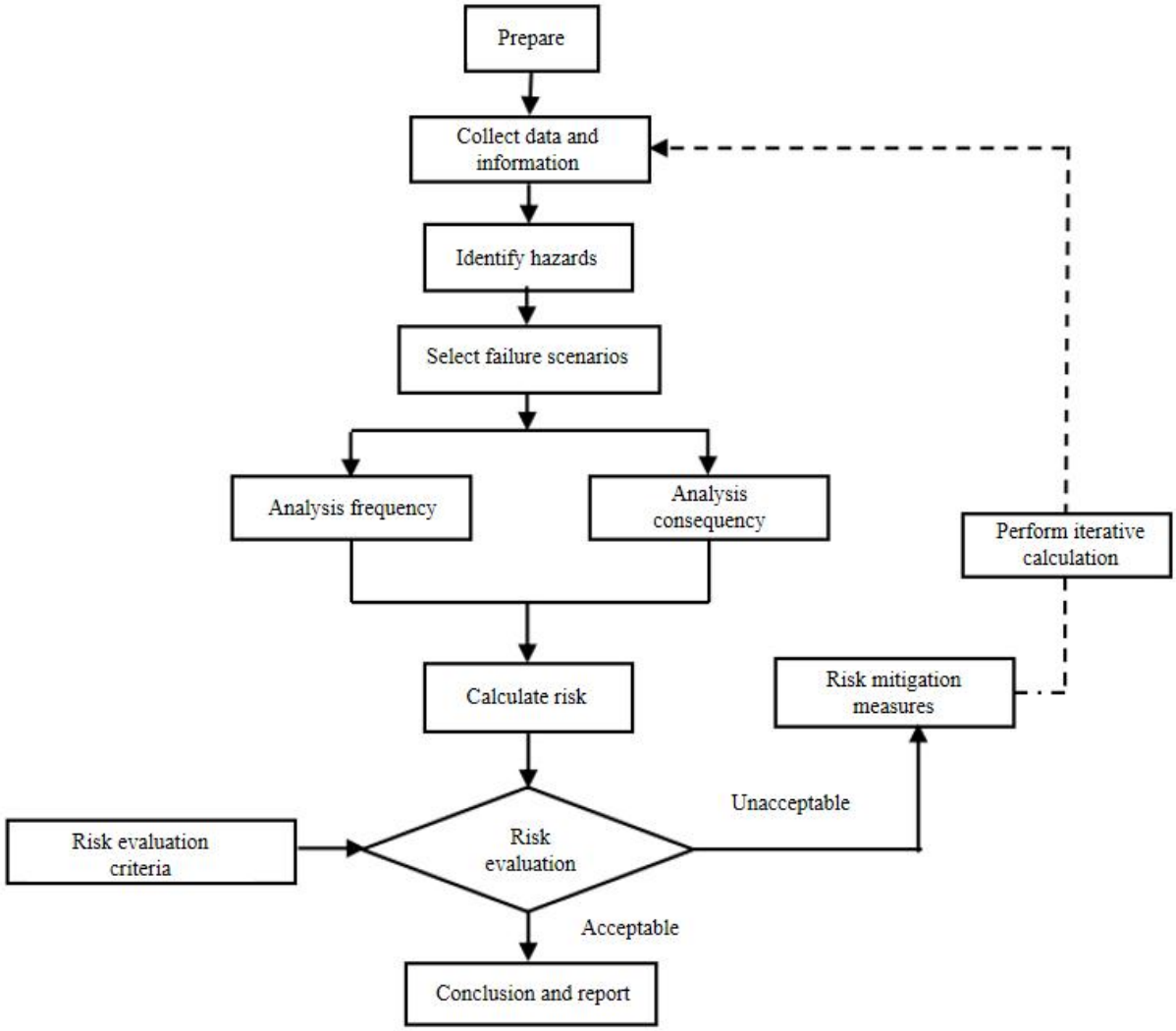



**Figure 2.3.1.2 Quantitative Risk Assessment Implementation Process**

### 2.3.2 Implementation process

2.3.2.1 In the preparation stage, the objective of the risk assessment and the analysis scenarios are to be defined, the assessment work team is to be formed, the information is to be collected and the work plan is to be arranged.

2.3.2.2 For hydrogen-powered ships, the objective of the risk assessment is to be determined according to the need for risk assessment. The following factors are to be taken into account when defining the scope of analysis:

(1) ship particulars (e.g. ship type, ship length, newbuilding or existing ship, etc.);

(2) ship systems (e.g. general arrangement, gas supply system, propulsion installation, etc.);

(3) ship operations (e.g. operation location, fuel bunkering mode, etc.);

(4) external effects on the ship (e.g. weather, hydrology, etc.);

(5) accident categories (e.g. collision, fire, explosion, etc.);

(6) consequence categories of risk (e.g. personal injury and/or death, damage to ship or port

facilities, etc.).

2.3.2.3 An assessment work team is to be formed and a team leader is to be designated. The assessment work team is to include, but is not limited to, professionals in ship safety, process, materials, electrical, instrumentation, equipment and process operation, as well as computational fluid dynamics (CFD) analysts. Work team members may participate in only part of the work according to the work content at different assessment stages, and provide necessary information and advice to the work team.

2.3.2.4 The team leader is to prepare a work plan for the project, determine the project objectives and scope of work according to the specific circumstances of the project and available resources, and be responsible for coordination among all parties during project execution.

2.3.2.5 Before the formal commencement of the assessment, the work team members are to assist the work team leader in formulating assessment rules as follows:

(1) risk acceptability criteria;

(2) data collection, processing and handling of missing data (e.g. interpolation, extrapolation, consolidation, etc.);

(3) records of assessment data, assumptions, processes and results;

(4) methods and principles for calculating frequency;

(5) methods and principles for calculating consequence;

(6) methods and principles for calculating risk.

2.3.2.6 The information and data to be collected are to be determined according to the objective and depth of the risk assessment. For hydrogen-powered ships, the information to be collected includes but is not limited to:

(1) ship-related drawings and information, such as general arrangement plan, process flow diagram (PFD), process piping and instrumentation diagram (P&ID), hazardous area classification plan, ventilation system arrangement plan, etc.;

(2) local meteorological and hydrological information at the operation site;

(3) required operating manuals;

(4) existing qualitative risk assessment reports (if any);

(5) records of previous accidents (if any);

(6) other information required.

2.3.2.7 For the QRA method for hydrogen-powered ships, refer to Chapter 6 of the Guidelines.

2.3.2.8 The quantitative risk assessment report is to contain at least the following:

(1) Cover: including project name, preparation organization, preparation date, etc.;

(2) Contents: listing the sections and page numbers of the report;

(3) Main text, including at least:

① Terms and abbreviations: explanation of professional terms and abbreviations used in the report (if applicable);

② Project overview: brief introduction to the purpose, background and basis of the report;

③ Scope of analysis: definition of the object, objectives and list of technical information of the analysis;

④ Hazard identification process: at least the contents of ③ to ⑦ of 2.2.2.11(3) of this chapter (if applicable);

⑤ Frequency and consequence analysis: including the frequency and consequence analysis process for each hazardous event, with definition of the input parameters, models and methods used;

⑥ Risk calculation: calculation process of individual risk value and societal risk value (if applicable);

⑦ Conclusions and recommendations: proposed risk reduction measures and recommendations based on the risk assessment results.

（4） Appendices, including at least:

① List of drawings, specifications, etc. used in the analysis;

② Attendance sheet of the hazard identification meeting (if applicable);

③ Hazard identification worksheets (if applicable).

# CHAPTER 3 APPLICATION OF HAZID FOR HYDROGEN-POWERED SHIPS

## Section 1 GENERAL PROVISIONS

### 3.1.1 Goal

3.1.1.1 The goal of HAZID analysis is to identify potential safety hazards that may exist in the existing design scheme and during operations of a ship, conduct qualitative analysis and assess their consequences, thereby determining reliable protection measures to reduce the impact in the event of an accident and to guide subsequent design, so as to make the project safer and more efficient.

### 3.1.2 General requirements

3.1.2.1 HAZID analysis is primarily used during the design stage of hydrogen-powered ships to conduct risk analyses on all shipboard hydrogen-related spaces and to propose risk mitigation recommendations. It may also be used for risk analysis of gas trial bunkering operations during the construction stage, fuel bunkering operations during the operational stage, and navigation in special scenarios (e.g., ship passing through locks or tunnels).

3.1.2.2 During HAZID analysis, the "What-If" method is typically used to identify hazards. When applying this method, realistic assumptions (guide words) should be proposed based on expert experience, so as to avoid scenarios that are practically impossible.

## Section 2 HAZID ANALYSIS PROCESS

### 3.2.1 Analysis process

3.2.1.1 The implementation process of HAZID includes study preparation, HAZID analysis and report preparation.

3.2.1.2 In the preparation stage of HAZID analysis, the objective and scope of the analysis are to be determined, the analysis team is to be formed, the basic information is to be collected, and meeting time and training are to be arranged.

(1) The scope of HAZID analysis is to be determined according to the object and purpose of the analysis. For example: for HAZID analysis of hydrogen-related spaces of a hydrogen-powered ship, the scope of analysis is the hydrogen-related spaces throughout the ship; for HAZID analysis of hydrogen bunkering operations of a hydrogen-powered ship, the scope of analysis is the whole process of hydrogen bunkering operations.

(2) The HAZID analysis team normally consists of a chairman, expert group members, a recorder and other personnel. The analysis team is to determine the guidewords applicable to the project according to the specific characteristics of the project.

(3) HAZID analysis is normally conducted under the guidance of the chairman. The chairman is to

be familiar with HAZID analysis techniques, have received professional training in HAZID analysis, and have good communication skills, meeting progress control capability and meeting room control capability. The HAZID analysis team members are to be familiar with the project background and understand the project scheme; persons with experience in similar projects are preferred.

(4) The type and level of detail of HAZID analysis information determine the depth of HAZID analysis. For hydrogen-powered ships, it is recommended that HAZID analysis be carried out at least after the preliminary design plan has been produced.

(5) In addition to drawings and information, the following are also to be collected as far as possible: previous accident situations, hazard analysis previously carried out for similar systems, standards and specifications applicable to hydrogen-powered ships, and relevant management regulations issued by the competent authority.

3.2.1.3 For HAZID analysis, the general arrangement plan or operational procedures are to be divided into several analysis nodes. The analysis team is to analyse each node using all guidewords in turn, analyzing the causes of accidents, possible consequences and existing safety measures, and giving recommended safety measures. The basic steps of HAZID analysis are shown in Figure 3.2.1.3 below.

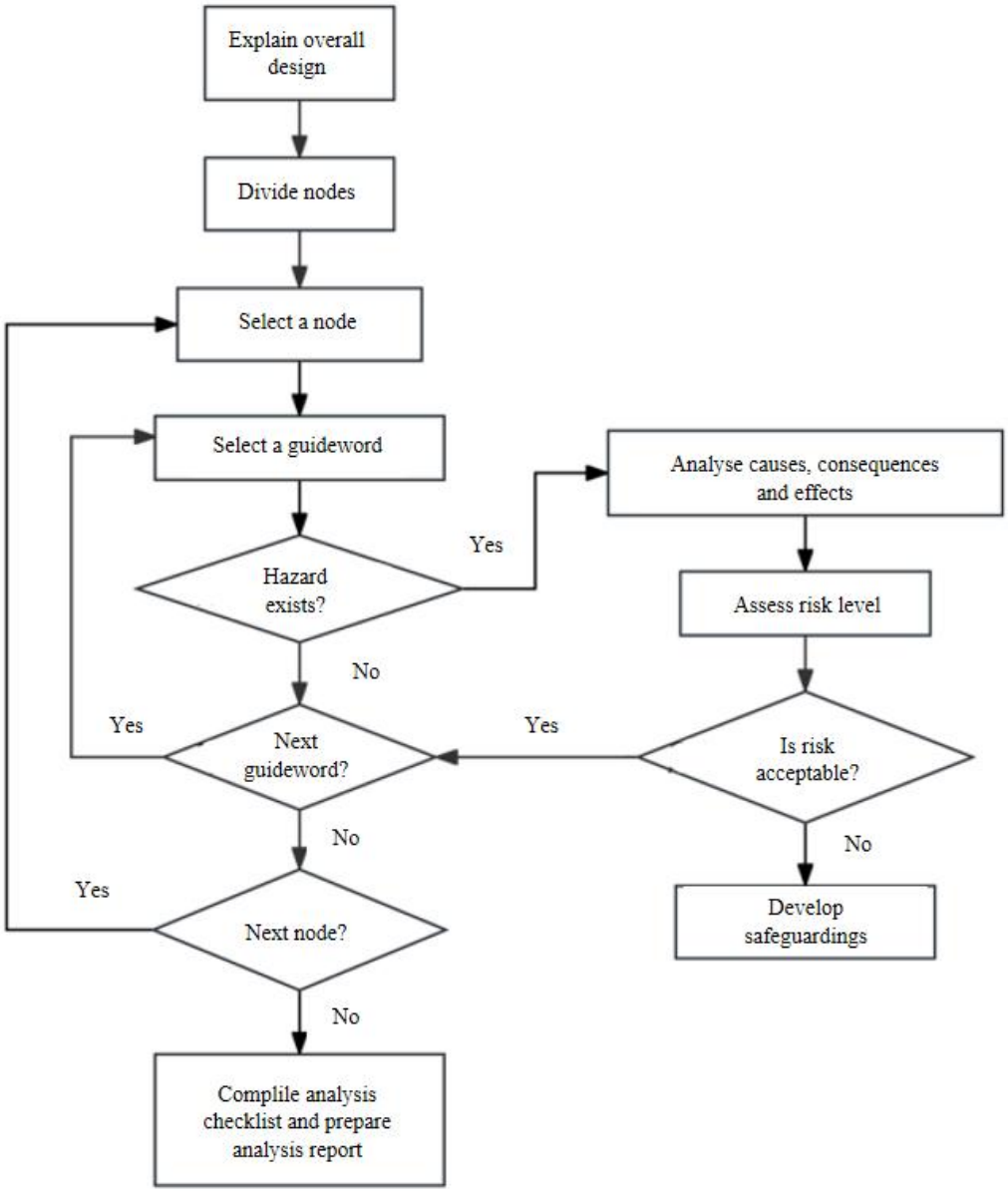



**Figure 3.2.1.3 HAZID Analysis Process**

(1) Node breakdown may be carried out according to functional blocks or process procedures. For example: for HAZID analysis of hydrogen-related spaces throughout the ship, nodes may be divided according to different spaces of the ship; for HAZID analysis of hydrogen fuel bunkering operations, nodes may be divided according to the operation procedures.

(2) Guidewords for hazard sources related to hydrogen-powered ships may refer to, but are not limited to, those listed in Table 3.2.1.3 of this chapter.

(3) During the analysis meeting, the chairman guides the team members to carry out "brainstorming" analysis for each node in the predetermined sequence of hazard source guidewords, discussing the causes of hazard sources, the effects or consequences caused, and identifying existing safety measures. The discussion content is to be recorded in the HAZID worksheet, see Appendix 1.1 of the Guidelines.

**HAZID Analysis Guidewords for Hydrogen-powered Ships** **Table 3.2.1.3**

| | |
|---|---|
| Collision | Machinery equipment failure |
| Grounding | Electric power system failure |
| Impact (falling objects, sea ice impact, etc.) | Control system failure |
| Fire/explosion | Communication system failure |
| Loss of power | Piping system (including valves, flanges and fittings) leakage and rupture |
| Loss of ship control (main engine, steering gear failure) | Pipeline blockage |
| Fuel containment system failure | Insufficient pre-cooling |
| Overpressure (overfilling) | Corrosion or wear |
| Rapid temperature rise | Manufacturing defects/material defects |
| Hydrogen embrittlement | Human factors/improper operation |
| Fatigue (stress and strain, vibration) | …… |

(4) After hazard identification, the risk ranking is also to be assessed according to the predetermined risk matrix. The determination of the risk ranking is to satisfy the requirements of 2.2.2.9 to 2.2.2.11, Section 2, Chapter 2 of the Guidelines.

(5) Recommended measures are to be proposed in accordance with the requirements of 2.2.2.10, Section 2, Chapter 2 of the Guidelines, to ensure that the risk is reduced to a level acceptable to the enterprise through the implementation of existing safety measures and recommended measures.

(6) The preparation of the HAZID analysis report is to satisfy the requirements of 2.2.2.12, Section 2, Chapter 2 of the Guidelines.

# Section 3 HAZID ANALYSIS OF TYPICAL SCENARIOS

### 3.3.1 HAZID analysis of typical scenarios

3.3.1.1 For HAZID analysis of hydrogen-related spaces on board a hydrogen-powered ship, the drawings and information required to be collected at least include the ship general arrangement plan, hydrogen fuel bunkering station arrangement plan, hydrogen fuel storage space arrangement plan, fuel cell space arrangement plan, etc.

3.3.1.2 Nodes are to be divided according to different spaces. The hydrogen-related spaces of a hydrogen-powered ship at least include hydrogen storage spaces, hydrogen fuel bunkering stations, fuel cell spaces, etc. Where the ship is provided with power batteries, the space in which the batteries are arranged is to be included in the analysis as a node.

3.3.1.3 The HAZID analysis team consists of the chairman, recorder and relevant professionals with extensive experience, covering disciplines of ship general arrangement, power systems, bunkering systems, fuel cell systems, hydrogen storage systems, hydrogen storage materials, etc.

3.3.1.4 During the analysis meeting, the analysis team is to analyse the causes, consequences, risk levels and existing safety measures of hazard sources caused by ship design arrangement, process flow, equipment failure and human operation, and propose recommended safety measures according to the risk ranking. Taking the fuel cell space as an example, part of its HAZID worksheet may refer to Appendix 2.1 of the Guidelines.

### 3.3.2 HAZID analysis of ship hydrogen fuel bunkering operations

3.3.2.1 For HAZID analysis of ship hydrogen fuel bunkering operations, the drawings and information required to be collected at least include the ship general arrangement plan, bunkering station arrangement plan, hazardous area classification plan, safety operation manual, environmental conditions at the bunkering location and bunkering facility information, etc.

3.3.2.2 Nodes are to be divided according to the operation procedures. The nodes of hydrogen fuel bunkering operations may normally be divided into the berthing and mooring stage, bunkering system connection and preparation stage, bunkering operation stage, and the stage of disconnection after completion of bunkering and departure from berth.

3.3.2.3 The HAZID analysis team consists of the HAZID chairman, recorder and relevant professionals with extensive experience, covering disciplines of ship general arrangement, bunkering systems, hydrogen storage systems, bunkering process, etc.

3.3.2.4 During the analysis meeting, the analysis team is to analyse the causes, consequences, existing safety measures and risk levels of hazard scenarios at each operation stage, and propose recommended safety measures according to the risk ranking. Taking the berthing and mooring stage as an example, part of its HAZID analysis may refer to Appendix 2.2 of the Guidelines.

# CHAPTER 4 APPLICATION OF HAZOP FOR HYDROGEN-POWERED SHIPS

## Section 1 GENERAL PROVISIONS

### 4.1.1 Goal

4.1.1.1 The goal of HAZOP analysis is to conduct safety analysis of the ship's process systems, identify the causes and consequences of hazard sources arising from process flow and operational deviations, analyse the existing safety measures, and propose recommended safety measures according to the risk level.

### 4.1.2 General requirements

4.1.2.1 HAZOP analysis is mainly used at the design stage of hydrogen-powered ships to conduct risk analysis of the hydrogen fuel supply system and bunkering system, so as to reduce the risk of the process systems from the design scheme. It may also be used at the ship operation stage to conduct risk analysis of the fuel bunkering process system.

## Section 2 HAZOP ANALYSIS PROCESS

### 4.2.1 Analysis process

4.2.1.1 The implementation process of HAZOP includes study preparation, HAZOP analysis and report preparation.

4.2.1.2 In the preparation stage of HAZOP analysis, the objective and scope of the analysis are to be determined, the analysis team is to be formed, the basic information is to be collected, and meeting time and training are to be arranged.

(1) The scope of HAZOP analysis is to be determined according to the object and purpose of the analysis. The scope of work is normally one process system, such as the ship's fuel supply system, fuel bunkering system, etc.

(2) The HAZOP analysis team consists of the HAZOP chairman, recorder and relevant professionals with extensive experience. The analysis team is to determine the deviations applicable to the project according to the specific characteristics of the project, including guidewords and parameters.

(3) The HAZOP chairman is to have extensive analysis experience and have received professional training in HAZOP analysis. The analysis team members are to be familiar with the project background and understand the project scheme; persons with experience in similar projects are preferred.

(4) The type and level of detail of HAZOP analysis information determine the depth of HAZOP analysis. For hydrogen-powered ships, it is recommended that HAZOP analysis be carried out after the process design has been completed.

(5) In addition to drawings and information, the following are also to be collected as far as possible: previous accident situations, hazard analysis previously carried out for similar systems, standards and

specifications applicable to hydrogen-powered ships, and relevant management regulations issued by the competent authority.

4.2.1.3 For HAZOP analysis, the process diagram or operating procedures are to be divided into several analysis nodes or process units. The analysis team is to analyse each node using all guidewords in turn to obtain the causes of deviations, consequences, protection devices and recommended measures. The basic steps of HAZOP analysis are shown in Figure 4.2.1.3 below.

(1) Node breakdown may be carried out according to the process flow or operation sequence. For example, for HAZOP analysis of the design scheme of the hydrogen fuel supply system and bunkering system, nodes may be divided according to the process flow into hydrogen fuel supply, hydrogen fuel bunkering, purging and inerting after bunkering, etc.

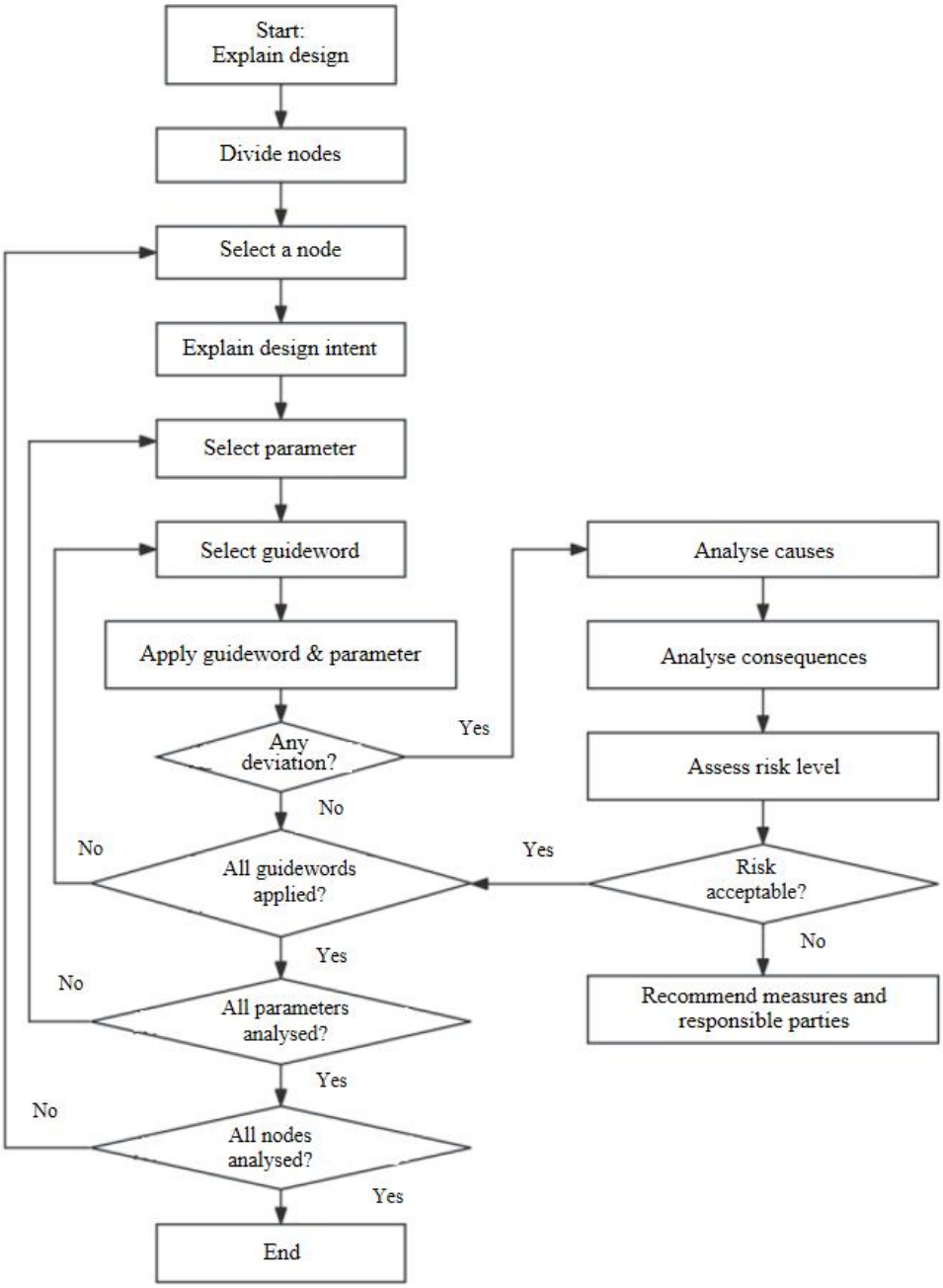



**Figure 4.2.1.3 HAZOP Analysis Process**

(2) For hydrogen-powered ships, the allowable deviations in the process are to be determined according to the object of analysis. Deviations are generated by the combination of guidewords and parameters. The process parameters related to hydrogen-powered ships are normally temperature, pressure, level, flow, composition and operation; the related guidewords are normally no, less (low), more (high), reverse, as well as. The guidewords and parameters include, but are not limited to, those listed in Table 4.2.1.3(1) of this chapter. For the meanings and usage of the guidewords, see Table 4.2.1.3(2) of this chapter.

(3) During the analysis meeting, the chairman guides the team members to carry out "brainstorming" analysis for each node in accordance with the predetermined deviations, discussing the causes of deviations, the effects or consequences caused, and identifying existing safety measures. The discussion content is to be recorded in the HAZOP worksheet, see Appendix 1.2 of the Guidelines.

(4) After hazard identification, the risk ranking is also to be assessed according to the predetermined risk matrix. The determination of the risk ranking is to satisfy the requirements of 2.2.2.9 to 2.2.2.11, Section 2, Chapter 2 of the Guidelines.

(5) Recommended measures are to be proposed in accordance with the requirements of 2.2.2.10, Section 2, Chapter 2 of the Guidelines, to ensure that the risk is reduced to a level acceptable to the enterprise through the implementation of existing safety measures and recommended measures.

(6) The preparation of the HAZOP analysis report is to satisfy the requirements of 2.2.2.12, Section 2, Chapter 2 of the Guidelines.

**HAZOP Guidewords for Hydrogen-powered Ships** **Table 4.2.1.3(1)**

| Parameter | No | Less (low) | More (high) | Reverse | As well as |
|---|---|---|---|---|---|
| Flow | No flow | Low flow | High flow | Reverse flow | Other phase |
| Level | No level | Low level | High level | — | — |
| Pressure | No pressure | Low pressure | High pressure | — | Pressure fluctuation |
| Temperature | — | Low temperature | High temperature | — | — |
| Composition | Gas-liquid two-phase, ingress of impurities | | | | |
| Operation | Opening/closing, incorrect operation, incorrect sequence | | | | |

**Meanings and Usage of Guidewords** **Table 4.2.1.3(2)**

| Guideword | Meaning | Comment |
|---|---|---|
| No | Complete negation of the design or operation intent. | The design requirements are not met at all, but no other condition occurs. |
| Less | Quantitative decrease of the relevant parameter compared with the design value. | Refers to quantities describing relevant physical properties, such as flow, temperature, etc. |
| More | Quantitative increase of the relevant parameter compared with the design value. | Refers to quantities describing relevant physical properties, such as flow, temperature, etc. |
| Reverse | Occurrence of something completely opposite to the design intent. | Mostly used to describe dynamic conditions, such as reverse flow of liquid, reaction proceeding in the opposite direction, etc. |
| Part of | Qualitative decrease of the relevant performance. | Only part of the intended function is accomplished, such as change in the proportion of components, absence of certain components, etc. |

| | | |
|---|---|---|
| As well as | Qualitative increase of the relevant parameter. | While the intended function is accomplished, additional events occur, such as phase change of fuel during bunkering, generation of static electricity, etc. |
| Other than | Departure from the normal design range. | Occurrence of something different from the design intent, such as abnormal events or states, change of operation mode, etc. |

# Section 3 HAZOP ANALYSIS OF TYPICAL SCENARIOS

### 4.3.1 HAZOP analysis of fuel supply system and bunkering system

4.3.1.1 For HAZOP analysis of the fuel supply system and bunkering system of a hydrogen-powered ship, the drawings and information required to be collected at least include the ship general arrangement plan, schematic diagram of the hydrogen fuel supply system, schematic diagram of the hydrogen fuel bunkering system, etc.

4.3.1.2 The fuel supply system and bunkering system of a hydrogen-powered ship may be divided into nodes according to the process flow, including hydrogen fuel supply, hydrogen fuel bunkering, purging and inerting after bunkering, etc. Taking a fuel cell powered ship using hydrogen cylinders as the fuel storage device as an example, its gas supply and bunkering system may be divided into the following nodes: high-pressure hydrogen bunkering, high-pressure hydrogen supply, low-pressure hydrogen supply, purging of the bunkering pipeline, etc.

4.3.1.3 The HAZOP analysis team consists of the chairman, recorder and relevant professionals with extensive experience, covering disciplines of ship power systems, bunkering systems, hydrogen storage systems, hydrogen storage materials, etc.

4.3.1.4 During the analysis meeting, the design personnel are first to fully explain the design intent of each node. The analysis team, under the guidance of the chairman, is to fully analyse the causes and consequences of deviations, identify existing safety measures, and propose recommended safety measures according to the risk level. Taking the high-pressure hydrogen supply node and the high-pressure hydrogen bunkering node as examples, part of the HAZOP worksheet may refer to Appendix 2.3 of the Guidelines.

# CHAPTER 5 APPLICATION OF FMEA FOR HYDROGEN-POWERED SHIPS

## Section 1 GENERAL PROVISIONS

### 5.1.1 Goal

5.1.1.1 The objective of FMEA is to identify risks and reduce failures at an early stage of equipment and system development by assessing potential failure modes, effects and solutions of equipment or systems, thereby improving product reliability.

### 5.1.2 General requirements

5.1.2.1 FMEA is mainly used for important equipment and process systems of hydrogen-powered ships, such as fuel cells, hydrogen-powered internal combustion engines and electric power systems, for risk analysis.

## Section 2 FMEA PROCESS

**5.2.1** FMEA process

5.2.1.1 The implementation process of FMEA includes planning and preparation, FMEA and report preparation.

5.2.1.2 Before carrying out FMEA, relevant planning and preparation are to be completed, including the following four main stages:

（1） **Define the objective and scope**: the scope and objective of the analysis are to be clarified, including determining the product or process to be analyzed and identifying the areas and problem points where risks need to be identified.

（2） **Form the FMEA team**: the FMEA team normally consists of core team members and extended team members. The core team may include the moderator, recorder, design engineer and design quality engineer; the extended team may include other professionals related to the equipment. The main responsibilities of the core team and the extended team are as follows:

① Under the guidance of the moderator, the core team members carry out FMEA work through the moderator's questions, the team members' answers and discussions.

② The extended team members assist the core team in analyzing specific aspects of the product and provide necessary professional knowledge.

（3） **Collect the required drawings and information**: FMEA requires sufficiently detailed data and information on the system and components in order to conduct meaningful analysis of the manner in which each component may fail. The data and information may include:

① drawings of the system and system components being analyzed, or flow charts of process steps;

② understanding of the function of each step in the process or each component of the system;

③ detailed information on process and environmental parameters that may affect operation;

④ understanding of the results of specific failures;

⑤ historical information on failures, including existing failure rate data.

（4） **Meetings and training**: the meeting plan is to be prepared and training is to be arranged for project participants to clarify the FMEA method and their respective responsibilities.

5.2.1.3 When carrying out FMEA on equipment, the object of analysis is to be defined, i.e. the definition of the indenture levels is to be clarified, the system is to be divided into components or steps, and the functional block diagram and reliability block diagram are to be prepared. The basic steps of FMEA are shown in Figure 5.2.1.3 below.

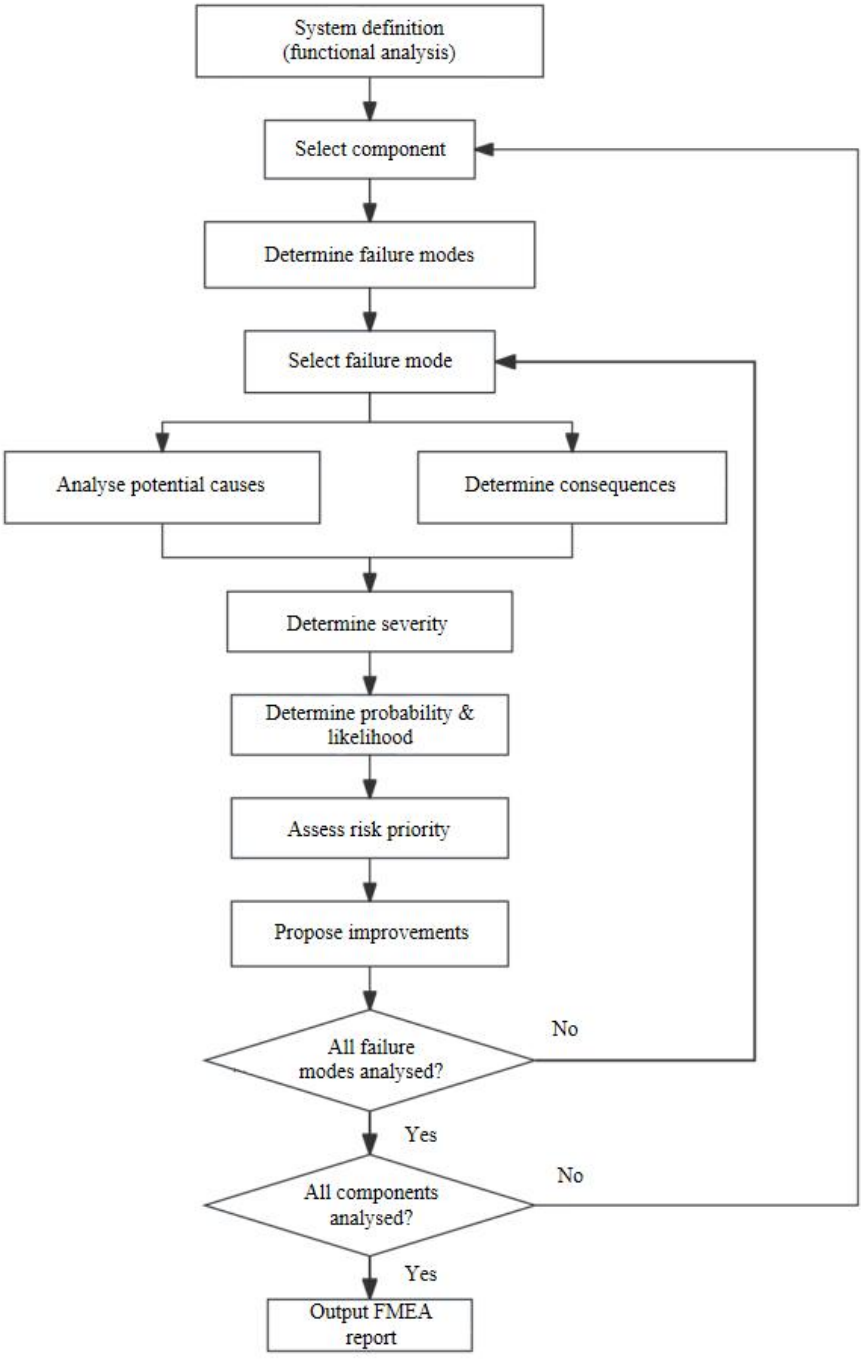



**Figure 5.2.1.3 FMEA Process**

5.2.1.4 For each component or step listed, the following are to be confirmed:

(1) define the failure criteria;

(2) analyse the failure modes and causes;

(3) failure effects and failure effect severity levels.

5.2.1.5 Failure criteria are the boundary values for judging whether the system constitutes a failure. Any non-human event that leads to the need for repair and causes failure is a failure event. Taking a 10 kW–70 kW low-temperature proton exchange membrane fuel cell and a 0 kW–40 kW solid oxide fuel cell as examples respectively, all software and hardware failures that affect the system's accomplishment of tasks are relevant failures. Accordingly, the performance parameters and allowable limits of the proton exchange membrane fuel cell and the solid oxide fuel cell, as well as their constituent devices, are specified in Table 5.2.1.5(1) and Table 5.2.1.5(2) of this chapter. These limits may be adjusted according to the actual product parameters of the fuel cell manufacturer.

**Example of Performance Parameters and Allowable Limits of a Low-temperature Proton Exchange Membrane Fuel Cell**

**Table 5.2.1.5(1)**

| Performance parameter | Unit | Specified requirement and allowable limit | Failure criterion |
|---|---|---|---|
| Power | kW | ≤70 | >75 |
| Voltage | V | 200～400 | ＜200 |
| | | | >400 |
| Hydrogen inlet pressure at stack | kPa | 15~90 | ＜10 |
| | | | >95 |
| Air inlet pressure at stack | kPa | 10~90 | ＜5 |
| | | | >95 |
| Pure water inlet temperature | ℃ | ≤75 | >80 |
| Pure water outlet temperature | ℃ | ≤85 | >85 |
| Hydrogen pressure in hydrogen supply line | MPa | 0.5~0.7 | ＜0.45 |
| | | | >0.75 |
| Ionic conductivity of pure water | μS/cm | ≤5 | >10 |
| Pressure in pure water circuit | MPa | 0.03~0.1 | ＜0.02 |
| | | | >0.11 |

**Example of Performance Parameters and Allowable Limits of a Solid Oxide Fuel Cell**

**Table 5.2.1.5(2)**

| Performance parameter | Unit | Specified requirement and allowable limit | Shutdown failure criterion |
|---|---|---|---|
| Power | A | 0~40 | ＞43 |
| Voltage | V | 230~350 | ＜230 |
| | | | ＞350 |
| Fuel gas header pressure | kPa | 100~200 | ＜50 |
| | | | ＞400 |

| Performance parameter | Unit | Specified requirement and allowable limit | Shutdown failure criterion |
|---|---|---|---|
| Air header pressure | kPa | 0~8 | ＞8 |
| Water buffer tank pressure | MPa | 0.45~0.55 | ＜0.4 |
| | | | ＞0.6 |
| Water branch pipe pressure | kPa | 0~250 | ＞250 |
| Stack air inlet temperature | ℃ | 660~680 | ＞700 |
| Stack air outlet temperature | ℃ | 700~730 | ＞750 |
| Temperature difference between air inlet and outlet | ℃ | ≤60 | ＞100 |
| Steam-to-carbon ratio | | 2~4 | ＜2 |
| | | | ≥4 |
| Operating voltage | V | 252~258 | ≤230 |
| Combustion flue gas temperature | ℃ | 800~880 | ＞900 |

5.2.1.6 The failure modes related to hydrogen fuel cells may refer to, but are not limited to, those listed in Table 5.2.1.6(1) and Table 5.2.1.6(2) of this chapter.

**Failure Modes of Low-temperature Proton Exchange Membrane Fuel Cells Table 5.2.1.6(1)**

| | |
|---|---|
| Low single-cell voltage | Output signal error |
| Hydrogen-air crossover | Membrane electrode assembly dry-out |
| Leakage | Over-temperature |
| High temperature | Humidification membrane perforation or cracking |
| Over-current | Decrease in water permeation rate of humidification membrane |
| Insufficient insulation | Decrease in water permeation rate of humidification membrane |
| Communication failure | Pressure out of control |
| Voltage detection abnormality | Failure to actuate |
| Control failure | Mechanical damage |
| Direct venting of hydrogen | Control system failure |
| No water drainage | Seal failure |
| Air inlet pressure outside the specified range | Hydrogen circulation component failure |
| Hydrogen inlet pressure outside the specified range | Thermal damage failure |

**Failure Modes of Solid Oxide Fuel Cells Table 5.2.1.6(2)**

| | |
|---|---|
| Low voltage | Output signal error |
| Large temperature difference between stack inlet and outlet | Carbon deposition in reformer |
| Leakage | Burner over-temperature |
| Stack over-temperature | Fuel gas flow abnormality |

| | |
|---|---|
| Over-current | Air flow abnormality |
| Insufficient insulation | Abnormal steam-to-carbon ratio |
| Communication failure | Fan control failure |
| Voltage detection abnormality | Pressure out of control |
| Control failure | Solenoid valve failure to actuate |
| Water tank level abnormality | Mechanical damage |
| Fuel gas buffer tank pressure abnormality | Control system failure |
| Conductivity abnormality | Seal failure |
| Burner flame-out | Cooling water pump failure |
| Insulation failure | ... |

5.2.1.7 During the analysis meeting, in order to identify all possible failure modes, causes and effects of the product in the functional and hardware design, the discussion content is to be recorded in the FMEA worksheet, see Appendix 1.3 of the Guidelines.

5.2.1.8 Criticality analysis is to be carried out to determine the relative magnitude of each failure effect and provide input for decision-making. The priority of measures to mitigate or eliminate specific failure effects may be determined by combining the severity of failure modes and the failure probability. The determination of the risk ranking is to satisfy the requirements of 2.2.2.9 to 2.2.2.11, Section 2, Chapter 2 of the Guidelines.

5.2.1.9 Design improvement measures and use compensation measures are to be proposed in accordance with the requirements of 2.2.2.10, Section 2, Chapter 2 of the Guidelines, to ensure that the risk is reduced to a level acceptable to the enterprise through the implementation of design improvement measures and use compensation measures.

5.2.1.10 The preparation of the FMEA report is to satisfy the requirements of 2.2.2.12, Section 2, Chapter 2 of the Guidelines.

# Section 3 FMEA OF TYPICAL SCENARIOS

### 5.3.1 FMEA of low-temperature proton exchange membrane fuel cells

5.3.1.1 For FMEA of low-temperature proton exchange membrane fuel cells of hydrogen-powered ships, the drawings and information required to be collected at least include the schematic diagram of the fuel cell module, etc.

5.3.1.2 The indenture levels are to be divided according to the functional relationship or compositional characteristics of the specific product of the low-temperature proton exchange membrane fuel cell. Taking a low-temperature proton exchange membrane fuel cell as an example, its indenture level diagram may refer to Appendix 2.4.1 of the Guidelines.

5.3.1.3 The functional block diagram of the low-temperature proton exchange membrane fuel cell system is to be prepared according to the composition of the product. Taking a low-temperature proton exchange membrane fuel cell as an example, its functional block diagram may refer to Appendix 2.4.2 of the Guidelines.

5.3.1.4 The reliability block diagram is to be prepared to characterize the functional logic relationship of the low-temperature proton exchange membrane fuel cell under the corresponding mission profile, visually presenting the logical correlation in which failure of a single unit or combined failure of multiple units leads to overall system failure. In view of the fact that failure of any unit in the low-temperature proton exchange membrane fuel cell system requires inspection or replacement and consequently generates corresponding maintenance and support work, the system is subject to a series reliability model. Taking a low-temperature proton exchange membrane fuel cell as an example, its reliability block diagram may refer to Appendix 2.4.3 of the Guidelines.

5.3.1.5 The FMEA team consists of the moderator, recorder, design engineer and relevant professionals with extensive experience, covering disciplines of proton exchange membrane fuel cells, ship power systems, equipment engineering, hydrogen storage systems, etc.

5.3.1.6 During the analysis meeting, the analysis team is to identify all possible failure modes, causes and effects of the low-temperature proton exchange membrane fuel cell in the functional and hardware design, and propose design improvement measures and use compensation measures for its weak links. Taking a low-temperature proton exchange membrane fuel cell as an example, part of its FMEA worksheet may refer to Appendix 2.4.4 of the Guidelines.

### 5.3.2 FMEA of solid oxide fuel cells

5.3.2.1 For FMEA of solid oxide fuel cells of hydrogen-powered ships, the drawings and information required to be collected at least include the schematic diagram of the fuel cell module, etc.

5.3.2.2 The indenture levels are to be divided according to the functional relationship or compositional characteristics of the solid oxide fuel cell. Taking a solid oxide fuel cell as an example, its indenture level diagram may refer to Appendix 2.5.1 of the Guidelines.

5.3.2.3 The functional block diagram of the solid oxide fuel cell system is to be prepared according to the composition of the product. Taking a solid oxide fuel cell as an example, its functional block diagram may refer to Appendix 2.5.2 of the Guidelines.

5.3.2.4 The reliability block diagram is to be prepared to characterize the functional logic relationship of the solid oxide fuel cell under the corresponding mission profile. Taking a solid oxide fuel cell as an example, its reliability block diagram may refer to Appendix 2.5.3 of the Guidelines.

5.3.2.5 The FMEA team consists of the moderator, recorder, design engineer and relevant professionals with extensive experience, covering disciplines of solid oxide fuel cells, ship power systems, equipment engineering, hydrogen storage systems, etc.

5.3.2.6 During the analysis meeting, the analysis team is to identify all possible failure modes, causes and effects of the solid oxide fuel cell in the functional and hardware design, and propose design improvement measures and use compensation measures for its weak links. Taking a solid oxide fuel cell as an example, part of its FMEA worksheet may refer to Appendix 2.5.4 of the Guidelines.

### 5.3.3 FMEA of the electric power system under navigation scenarios

5.3.3.1 For FMEA of the electric power system under navigation scenarios, the drawings and information required to be collected at least include the schematic diagram of the electric power system, etc.

5.3.3.2 The indenture levels are to be divided according to the functional relationship or compositional characteristics of the electric power system. For the indenture level division of the electric power system under navigation scenarios, reference may be made to Appendix 2.6.1 of the Guidelines.

5.3.3.3 The electric power system under navigation scenarios is to be divided into components or steps according to the composition of the system, and the functional block diagram is to be prepared. Taking an

electric power system under a navigation scenario as an example, its functional block diagram may refer to Appendix 2.6.2 of the Guidelines.

5.3.3.4 The reliability block diagram is to be prepared to characterize the functional logic relationship of the electric power system under navigation scenarios under the corresponding mission profile. In view of the fact that failure of any unit in each branch of the electric power system requires inspection or replacement and consequently generates corresponding maintenance and support work, the system is subject to a series reliability model. However, for an electric power system composed of multiple branches, where the branches are mutually redundant/backup, failure of any unit in a branch does not require repair or replacement; therefore, such a system model is a parallel model. Taking an electric power system under a navigation scenario as an example, the reliability block diagram of its branch model may refer to Appendix 2.6.3 of the Guidelines.

5.3.3.5 The FMEA team consists of the moderator, recorder, design engineer and relevant professionals with extensive experience, covering disciplines of ship electric power systems, equipment engineering, safety engineering, etc.

5.3.3.6 During the analysis meeting, the analysis team is to identify all possible failure modes, causes and effects of the product in the functional and hardware design, and propose design improvement measures and use compensation measures for its weak links. Taking an electric power system under a navigation scenario as an example, part of its FMEA worksheet may refer to Appendix 2.6.4 of the Guidelines.

# CHAPTER 6 APPLICATION OF QRA FOR HYDROGEN-POWERED SHIPS

## Section 1 GENERAL PROVISONS

### 6.1.1 Goal

**6.1.1.1** The goal of QRA is to quantitatively analyse the frequency and consequence of various accidents occurring in the ship itself or during its bunkering operations, to assist the relevant parties in better understanding the risks to which they are exposed, so as to implement more targeted risk control measures and provide input information for decision-making.

### 6.1.2 General requirements

**6.1.2.1** QRA is mainly used at the design stage of hydrogen-powered ships to conduct risk analysis of hydrogen dispersion, asphyxiation, fire or explosion in spaces where hydrogen leakage may occur, so as to reduce the risk of arrangement, structure and process systems from the design scheme. It may also be used at the ship operation stage to conduct analysis of the fuel bunkering process.

### 6.1.3 QRA implementation process

**6.1.3.1** The implementation process of QRA mainly includes data collection, hazard source identification, quantitative analysis of accident scenario frequency and consequence, risk calculation and evaluation. For the specific process, refer to Section 3, Chapter 2 of the Guidelines.

## Section 2 HAZARD IDENTIFICATION AND SCENARIO SELECTION

### 6.2.1 Hazard identification and failure scenario selection

6.2.1.1 For the implementation process and specific analysis methods of hazard identification, refer to Section 2, Chapter 2, Chapter 3, Chapter 4 and Chapter 5 of the Guidelines.

6.2.1.2 For the items in the hazard identification results that remain high risk after existing protection measures, where it is difficult to derive practical risk mitigation measures based on previous experience or to judge the effect of risk mitigation measures, they are normally used as quantitative risk assessment scenarios.

# Section 3 FREQUENCY ANALYSIS

### 6.3.1 Historical data

6.3.1.1 The following data sources are available for historical data:

(1) statistical results of historical failure data collected by the competent authority, organizations or enterprises;

(2) other databases recommended by the owner;

(3) other data sources[③].

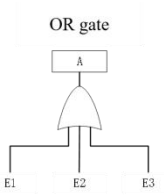
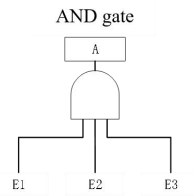
6.3.1.2 When using historical data, attention is to be paid to the applicability of the data source. Where necessary, scientific data processing methods may be considered for probability model validation.

### 6.3.2 Fault tree analysis

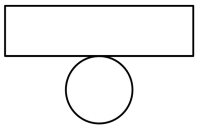
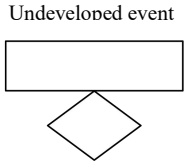
6.3.2.1 Fault tree analysis is commonly used to quantify the probability of the top event occurring, based on estimates of the failure frequency of each component. The top event may be an individual failure event, or a branch in an event tree.

6.3.2.2 The fault tree is usually built by gate-by-gate method, which quantifies all intermediate events in the fault tree and allows visual observation of the main contributors of the top event and the effect of safety measures in the fault tree. Construction usually starts with the top event, and works down towards the basic events. For each event, it is necessary to consider the conditions necessary to produce the event and the relationship with the event at the next level up. If any one of several events may cause the higher event, they are joined with an OR gate. If two or more events must occur in combination, they are joined with an AND gate. Typical symbols used in fault tree analysis are shown in Table 6.3.2.2 of this chapter.

**Common Symbols for Fault Tree Analysis** **Table 6.3.2.2**

| | Symbol | Description |
|---|---|---|
| Logic gates |  | An OR gate means that the top event A occurs as long as any one of the input events occurs. |
| |  | An AND gate means that the top event A occurs only when all input events occur simultaneously. |

③ The HyCReD project jointly carried out by the National Renewable Energy Laboratory, the University of Maryland and other hydrogen energy stakeholders; the H2 Tools Lessons Learned database of the U.S. Department of Energy; the HySafe project of the European Union and the Hydrogen Incidents and Accidents Database (HIAD) project database of the Joint Research Centre of the European Commission; the Center for Hydrogen Safety (CHS) project database of the American Institute of Chemical Engineers; the hydrogen failure and accident database of Sandia National Laboratories; etc.

| | Symbol | Description |
|---|---|---|
| Input events | Basic event  | A basic event represents a basic equipment failure that does not require further subdivision of failure causes. |
| | Undeveloped event  | An undeveloped event represents an event that does not require further analysis due to lack of information or insignificant consequences. |

6.3.2.3 Some types of event (e.g. a fire or power failure) may affect many components in the system at once. These are known as "common-cause failures", and may be represented by having the same basic event occurring at each appropriate place in the fault tree.

6.3.2.4 Taking the hydrogen leakage event of a fuel cell as an example, the fault tree analysis example may refer to Figure 6.3.2.4 of this chapter.

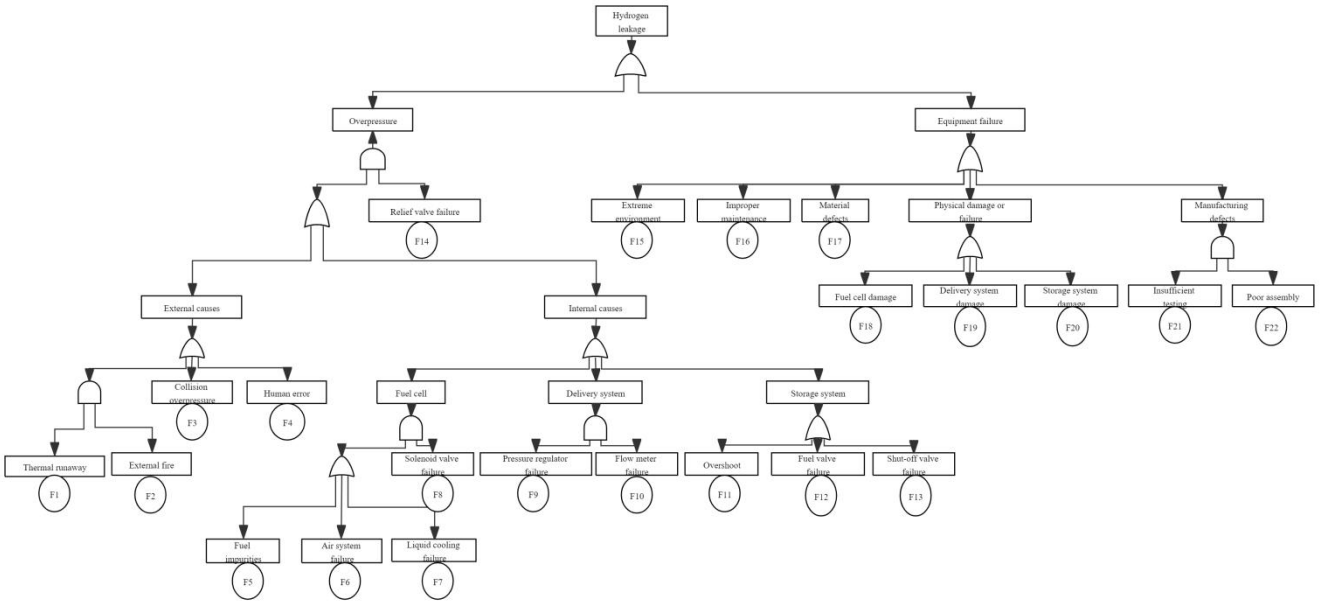



**Figure 6.3.2.4 Example Fault Tree for Hydrogen Leakage from a Fuel Cell**

6.3.2.5 Combination of frequency and probability

Both frequencies and probabilities can be combined in a fault tree, providing the rules in Table 6.3.2.5 of this chapter are followed.

**Rules for Combining Frequencies and Probabilities** **Table 6.3.2.5**

| Gate | Inputs | Outputs |
|---|---|---|
| OR | Probability + Probability | Probability |
| | Frequency + Frequency | Frequency |
| | Frequency + Probability | Not permitted |
| AND | Probability × Probability | Probability |
| | Frequency × Frequency | Not permitted |
| | Frequency × Probability | Frequency |

6.3.2.6 Quantification of a fault tree

Simple fault trees may be analyzed using a gate-by-gate approach to determine the top event probability, provided that all events are independent and there are no common-cause failures. If the input probabilities are small (<0.1), the OR and AND gates are evaluated as follows:

OR gate:

$$P（A） = \sum_{i=1}^{N} \mathrm{P}(B_i)$$

AND gate:

$$P（A） = \prod_{i=1}^{N} P(B_i)$$

where,

*P(A)*= output event probability;

*P(Bi)*= input event probability;

*N*= number of input events.

If the input probabilities are not small, the OR and AND gates may be evaluated as follows:

OR gate:

$$P(A) = P(B_1) + P(B_2) - P(B_1)\,P(B_2)$$

$$= 1 - (1 - P(B_1))\,(1 - P(B_2))$$

AND gate:

$$P(A) = P(B_1) \times P(B_2)$$

### 6.3.3 Event tree analysis

6.3.3.1 An event tree may be used to analyse how the initial triggering event of an accident develops along different paths, ultimately leading to multiple possible consequences.

6.3.3.2 Determine the analysis objective and the initiating event

Clarify the objective of the risk assessment: before starting the event tree analysis, it is first necessary to clarify the objective of the assessment, such as assessing the safety of a system in the event of a fault, or analyzing the development path and consequences of a specific accident (e.g. high-pressure hydrogen leakage in the hydrogen fuel cylinder storage room).

Determine the initiating event: the initiating event is the starting point of the entire event tree analysis, normally the occurrence of an accident or fault (e.g. equipment failure, operational error or external impact, ageing of the cylinder sealing gasket, etc.). This event triggers a series of subsequent responses and protective measures.

6.3.3.3 Construct the event tree

Construct the tree diagram structure: starting from the initiating event, a top-down tree diagram is drawn, with each branch representing a key turning point. Each node represents an event that may occur at a specific moment, such as whether the safety system operates as expected, whether emergency measures are activated in time, etc.

Branch node setting: binary branches (normal/abnormal or ignited/not ignited, etc.) are commonly used, but in practical applications, multiple branches may also be set as required.

Logical sequence and time axis: the branches of the event tree are to be arranged in chronological order of accident development, reflecting the causal chain from the initiating event to the final result. Each branch node is to be consistent with the physical or management process of the system.

6.3.3.4 Taking the leakage event of a high-pressure hydrogen cylinder as an example, the event tree analysis example may refer to Figure 6.3.3.4 of this chapter.

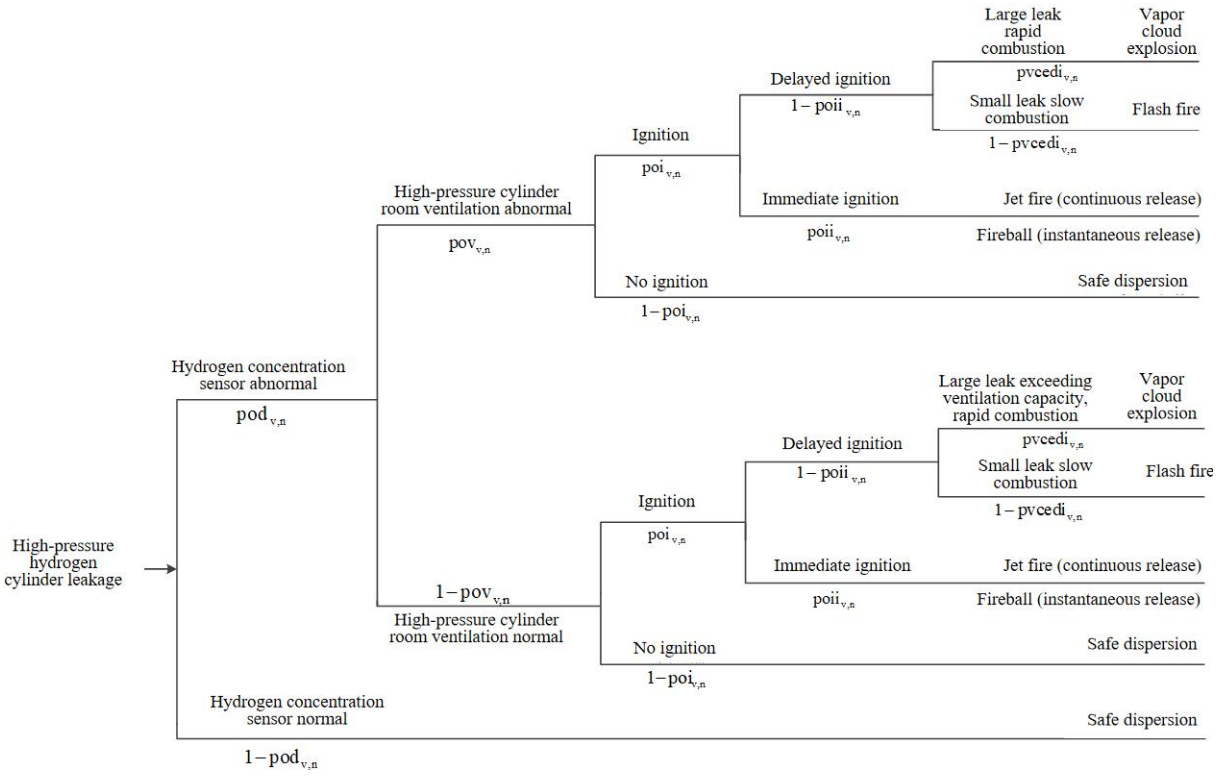



**Figure 6.3.3.4 Example Event Tree for Hydrogen Leakage from a High-pressure Hydrogen Cylinder**

6.3.3.5 Quantification of the event tree

（1） Assign probability to branch nodes: a probability of occurrence is to be assigned to each key event node based on historical data, equipment failure rates, expert experience or experimental data. For example, the failure probability of a hydrogen concentration sensor may be 0.02, while the probability of successful detection is 0.98 (the values shown in the figure above are the corresponding probabilities).

（2） Calculate path probability: a probability is associated with each branch, being the conditional probability of the branch condition occurring (i.e. the probability of the answer "yes" or "no" to the branch question). In each case, the sum of the probabilities of each branch must be unity. The probability of each outcome is calculated from the following formula:

$$P（A）=\prod_{i=1}^{N} P(B_i)$$

where,

$P(A)$= outcome probability;

$P(B_i)$= branch probabilities on route to outcome;

$N$= number of branches on route to outcome.

In general, the sum of all outcome probabilities must be equal to 1:

$$\sum_{j=1}^{M} P（A_j）=1$$

where,

$P(A_j)$= outcome probability;

$M$= number of outcomes.

If the frequency of the initiating event is specified (e.g. F), the frequency of each outcome is calculated by the following formula:

$$F（A_j）=F \times P（A_j）$$

where,

$F$= initiating event frequency;

$F(A_j)$= outcome frequency.

# Section 4 CONSEQUENCE ANALYSIS

### 6.4.1 Types of hydrogen accident disaster consequences

6.4.1.1 General types of hydrogen accident disaster consequences

（1） Leakage

① Leakage is a prerequisite for the formation of disaster. Depending on the type and nature of the leaking substance, the leakage rate, the time of ignition and the surrounding environment, various disaster events such as dispersion, fire and explosion may occur;

② Typical hydrogen leakage may normally be divided into: continuous gas leakage, continuous liquid leakage and two-phase leakage.

（2） Dispersion

③ Dispersion may be divided into liquid pool dispersion and gas dispersion according to the phase state of the leaking substance;

④ When liquid hydrogen/hydrogen leaks under the action of gravity or pressure, a liquid pool or gas cloud is formed. The process may be divided into instantaneous leakage and continuous leakage. The evaporation model is to be taken into account when calculating the liquid pool formed.

（3） Explosion

In professional standards④, explosion is divided into deflagration and detonation. When hydrogen/liquid hydrogen vapour/hydrogen storage material dust mixes with air and is ignited, subsonic combustion occurs, which is normally referred to as deflagration. The flame of deflagration propagates through heat conduction and convection at a relatively low speed (normally 1–100 m/s, below the speed of sound). When the combustible substance mixes with air and is ignited, due to certain special reasons or conditions, the flame propagates at an accelerated rate and supersonic combustion occurs, forming a strong shock wave, which is normally referred to as detonation. The flame propagation speed is extremely high (up to 1500 m/s or higher, far exceeding the speed of sound). In actual accidents, more than 90% of "explosions" are actually deflagrations (subsonic).

The main types of explosion are the following three:

① Confined explosion (or confined-vented explosion): the space in which the burning gas is located is largely confined, normally occurring in hollow enclosed spaces, such as inside tanks or in enclosed/semi-enclosed spaces of a ship. The main mechanism of pressure build-up is the volumetric expansion of the gas as it burns, exceeding the vent capacity of the space;

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④ In standards such as NFPA 68 and CCPS Guidelines for Hazard Evaluation, a clear distinction is drawn between deflagration and detonation, the former being subsonic and the latter supersonic.

② Open space explosion: the gas cloud is largely unconfined (e.g. above the upper deck or the sea surface), but there are sufficient obstacles to generate turbulence and accumulate pressure. This is also known as an "unconfined vapour cloud explosion" (UVCE), which may occur in spaces without any obvious confinement;

③ Semi-confined explosion: an explosion occurring between a confined explosion and an open space explosion, where part of the gas is in a confined condition.

6.4.1.2 Types of disaster consequences for high-pressure hydrogen storage

(1) Jet fire (or torch): when pressurized hydrogen leaks, a jet is formed and is ignited at the leakage opening, thereby forming a jet fire. The length of the jet flame mainly depends on the jet velocity of the fuel, and the jet velocity depends on the pressure and the aperture causing the leak.

(2) Flash fire: combustion of combustible gas without overpressure is called flash fire. The duration of flash combustion is relatively short, which may then evolve into a continuous jet fire at the leakage source, gradually stabilizing to form a jet fire.

(3) Fireball: the phenomenon that occurs when a large amount of fuel burns with a limited mixture of surrounding air is called a fireball.

6.4.1.3 Types of disaster consequences for liquid hydrogen storage

(1) Pool fire: after liquid hydrogen leakage flows to the ground to form a liquid pool, or flows to the water surface and covers the water surface, it meets a fire source and burns to form a pool fire. The pool fire model is applicable to fires mainly controlled by fuel (i.e. not subject to other restrictions, such as space and oxygen).

(2) Rapid phase transition (RPT): when leaked cryogenic liquid comes into contact with water, it evaporates rapidly and violently. This process is called rapid phase transition (RPT). The RPT phenomenon may cause a physical explosion (non-combustion) and generate overpressure shock waves.

(3) Flash evaporation: when liquid hydrogen leaks from a high-pressure environment to an atmospheric/low-pressure environment, or when cryogenic liquid hydrogen comes into contact with the surface of an object at ambient temperature, instantaneous and violent partial vaporization occurs due to the sudden pressure drop and relatively superheated temperature. This process forms a two-phase cloud containing cryogenic liquid and hydrogen, and significantly affects the hydrogen dispersion distance and the extent of cryogenic hazardous areas.

(4) Air condensation: when liquid hydrogen comes into contact with air, water vapour, carbon dioxide and other impurities in the air condense and solidify upon cooling. The solid impurities may block pipelines, filters and valves, causing failure of protective devices. Solid oxygen particles may cause the system to explode and ignite.

(5) Oxygen-enriched environment: after liquid hydrogen or cold energy leakage, nitrogen in the air around the tank condenses to form an oxygen-enriched environment.

6.4.1.4 Types of disaster consequences for metal hydride hydrogen storage

(1) Dust explosion: during the pulverisation of hydrogen storage alloys, if the alloy powder or its hydride is exposed to air, there is a risk of dust explosion. In alloy powder explosion experiments, it has been found that the smaller the powder particle size, the greater the possibility of explosion and the greater the pressure generated by the explosion.

(2) Overpressure failure: when the temperature of the solid-state hydrogen storage system is excessively high, the hydrogen pressure in the system may rise sharply, leading to pressure-bearing failure.

### 6.4.2 Consequence calculation

6.4.2.1 Leakage calculation model

(1) The initial leakage rate mainly depends on the internal pressure of the equipment, the leakage size and the phase state of the medium.

(2) When carrying out quantitative calculation of leakage scenarios, the leakage aperture is to be set according to the specific equipment. The leakage aperture of each equipment may be selected by referring to the industry database. If there is no special requirement or clear selection standard for leakage aperture, reference may be made to Table 6.4.2.1 of this chapter for selection.

**Example of aperture-based leak size definition for hydrogen equipment** **Table 6.4.2.1**

| Equipment | Size |
|---|---|
| Pipe | 0.01 $D^2$ ($mm^2$) for $D \leq 100$ mm, 100 $mm^2$ for $D > 100$ mm |
| Flange | Blow-out of gasket: $\pi Dt/4$ |
| Valve | Bonnet failure when bolts are used for fastening: bonnet area = $\pi DBt/4$ |
| Hose | Full-bore rupture: $\pi D^2/4$ |
| Pipe coupling and screwed connections | Full-bore rupture: $\pi D^2/4$ |
| Note: In the table, $D$ is the pipe diameter, $t$ is the gasket thickness, and $DB$ is the bolt diameter. | |

(3) When the leakage aperture is difficult to determine, the leakage rate may be used instead, but this method cannot take into account the variation of working pressure.

(4) The above factors are to be fully considered when calculating the leakage rate. For the specific calculation formulae, reference may be made to recognized standards⑤.

6.4.2.2 Dispersion calculation model

(1) At present, there are several evaluation models for gas dispersion calculation, mainly including the Gaussian model, HMP model, BM model, plate model, box model, etc.

(2) When calculating the dispersion range, the calculation model is to be selected according to the actual scenario. For the specific calculation process, reference may be made to recognized standards⑤.

6.4.2.3 **Jet fire calculation model**

(1) For jet fire calculation, reference may be made to recognized standards⑤.

(2) The prediction of the thermal radiation field around the flame is relatively complex. If the convective heating effect of the jet flame on obstacles is to be considered, computational fluid dynamics (CFD) may be used for a more detailed prediction.

6.4.2.4 **Pool fire calculation model**

(1) The calculation of pool fire mainly involves parameters such as the pool radius, burning rate and thermal radiation. For the specific calculation, reference may be made to recognized standards⑤.

(2) Dynamic pool fires occur in flowing liquid and may be predicted using computational fluid

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⑤ Such as the Netherlands organization for Applied Scientific Research (TNO), Methods for the Calculation of Physical Effects ('Yellow Book'), GB/T 37243 Determination Method of External Safety Distance for Hazardous Chemicals Production Units and Storage Installations, etc.

dynamics (CFD).

6.4.2.5 **Flash fire calculation model**

For the specific calculation of flash fire, reference may be made to recognized standards⑥, and computational fluid dynamics (CFD) may also be used for prediction.

6.4.2.6 **Fireball calculation model**

For the fireball calculation model, reference may be made to recognized standards⑥, and computational fluid dynamics (CFD) may also be used for prediction.

6.4.2.7 **Explosion calculation model**

For the explosion calculation model, reference may be made to recognized standards⑥, and computational fluid dynamics (CFD) may also be used for prediction.

6.4.2.8 When calculation software is used for consequence analysis, calculation software widely accepted by the industry is to be used, and the applicable working conditions of the software are to be considered, so as to ensure the certainty and confidence of the calculation results.

### 6.4.3 Disaster acceptance criteria

6.4.3.1 The acceptance criteria for disaster may refer to the criteria set out in 6.4.3.2 to 6.4.3.7 of this chapter.

6.4.3.2 The acceptance criteria for hydrogen dispersion concentration may refer to Table 6.4.3.2 of this chapter.

**Acceptance Criteria for Hydrogen Dispersion Concentrations** **Table 6.4.3.2**

| Hydrogen dispersion | Volumetric concentration | Remarks |
|---|---|---|
| | 2% | 50% of the lower flammable limit of hydrogen |

6.4.3.3 The acceptance criteria for fire heat radiation may refer to Table 6.4.3.3 of this chapter.

**Acceptance Criteria for Fire Heat Radiation** **Table 6.4.3.3**

| Max. intensity of thermal radiation ($kW/m^{2)}$) | Max. thermal dose of thermal radiation $(kW/m^2)^{4/3} \cdot s$ | Remarks |
|---|---|---|
| 5.0 | 500 | In the event of not less than 10% of skin exposure to a fire for 30 seconds, second-degree burns to at least 10 persons. |
| 5.0 | 300 | In the event of not less than 10% of skin exposure to a fire for 30 seconds, second-degree burns to at least one person in the building. |
| 32 | N/A | Loss of strength (significantly decreased loading capacity) of steel structures exposed to a fire during sustained burning. |

⑥ Such as the Netherlands organization for Applied Scientific Research (TNO), Methods for the Calculation of Physical Effects ('Yellow Book'), GB/T 37243 Determination Method of External Safety Distance for Hazardous Chemicals Production Units and Storage Installations, etc.

Note: The maximum thermal dose of thermal radiation is the cumulative thermal radiation dose, calculated as $Q=\int_0^t Q^{4/3}dt$, being the time integral of the heat flux (weighted by the 4/3 power).

6.4.3.4 The acceptance criteria for blast shock wave may refer to Table 6.4.3.4 of this chapter.

**Acceptance Criteria for Blast Shock Wave** **Table 6.4.3.4**

| Overpressure corresponding to damage ($N/m^2$) | | Overpressure damage |
|---|---|---|
| Lower limit | Upper limit | |
| 250 | 4000 | Glass window damage |
| 5000 | 10000 | Damage to doors and cladding, and personnel injury |
| 15000 | 20000 | Severe structural damage to buildings |
| 25000 | 50000 | Serious casualties |

6.4.3.5 **Probability of death due to thermal radiation**

(1) The probability of death due to fireball, pool fire and jet fire may be calculated by the following formula:

$$P_r = -36.38 + 2.56\ln\left(Q^{4/3} \times t\right)$$

where,

$P_r$ — probability of death under thermal radiation exposure;

$Q$ — heat radiation intensity, in $W/m^2$;

$t$ — exposure time, in s, with a maximum of 20 s.

(2) In calculating the death probability of thermal radiation exposure, the death probability of personnel is 100% when they are in the fireball, pool fire and jet fire scenes or when the thermal radiation intensity is not less than 37.5 $kW/m^2$. The probabilities of death caused by different thermal radiation intensities are shown in Table 6.4.3.5 of this chapter.

**Probabilities of Death due to Thermal Radiation Intensities** **Table 6.4.3.5**

| Thermal radiation intensity ($kW/m^2$) | Probability of death | Remarks |
|---|---|---|
| 37.5 | 1% (10 s); 100% (1 min) | Damage to operating equipment |
| 25.0 | Heavy burn (10 s); 100% (1 min) | Minimum amount of energy required for wood to burn under non-flame, long-duration radiation |
| 12.5 | First-degree burn (10 s); 1% (1 min) | Minimum energy for wood burning and plastic melting when there is a flame |
| 6.3 | Pain on bare skin within 8 s; when there is no thermal radiation shielding facility, the operator may stay for 1 min in protective clothing | — |
| 4.7 | Pain on bare skin after exposure for 16 s; when there is no thermal radiation shielding facility, the operator may stay for several minutes in protective clothing | — |
| 1.58 | No discomfort under long-duration exposure | — |

6.4.3.6 Probability of death due to flash fire and explosion overpressure

The flame area of a flash fire is the extent when hydrogen is ignited at its lower flammable limit (LFL). Within the flash fire flame area, the probability of death is 100%; outside the flash fire flame area, the probability of death is 0.

For vapour cloud explosion, within the area affected by 0.03 MPa overpressure, the probability of death is 100%; outside the area affected by 0.01 MPa overpressure, the probability of death is 0.

6.4.3.7 Criteria for asphyxiation by oxygen/hydrogen concentration

Asphyxiation mainly takes into account the effect of the decrease in oxygen concentration after hydrogen enters the air. The criteria for asphyxiation by oxygen/hydrogen concentration are shown in Table 6.4.3.7 of this chapter.

**Criteria for Asphyxiation by Oxygen/Hydrogen Concentration Table 6.4.3.7**

| Oxygen concentration | Hydrogen concentration | Condition | Source |
|---|---|---|---|
| 8% | 62% | Death within a very short time | International Maritime Organization (IMO), "Ship Safety Manual" |

# Section 5 RISK EVALUATION

### 6.5.1 Calculation grid

6.5.1.1 Before the calculation of individual risk and societal risk, a grid of the calculation area is to be defined.

6.5.1.2 The population density within a grid cell is assumed to be constant.

6.5.1.3 The size of the grid cell is to be as small as possible to reduce its influence on the calculation results.

### 6.5.2 Calculation of individual risk value

6.5.2.1 The individual risk calculation procedure is shown in Figure 6.5.2.1 of this chapter, and the steps are as follows:

(1) Select a leak scenario (*LOC*) and determine the frequency of occurrence $f_s$ of the *LOC*;

(2) Select a weather class *M* and a wind direction $\varphi$ under the weather class, and give the joint probability $P_M \times P_\phi$ of the simultaneous occurrence of the weather class *M* and the wind direction $\varphi$;

(3) For combustible leakage, select an ignition event *i* and determine the ignition probability $P_i$. Where toxic effects of the substance are considered, the ignition event is not considered;

(4) Calculate the probability of death $P_{IR}$ on a grid cell under the conditions of the specific *LOC*, weather class *M*, wind direction $\varphi$ and ignition event *i* (combustible);

(5) Calculate the contribution to the individual risk of the grid cell under the conditions (*LOC*, *M*, $\varphi$, *i*);

$$\Delta IR_{S,M,\varphi,i} = f_S \times P_M \times P_\varphi \times P_i \times P_{IR}$$

(6) Repeat the calculation of steps (3) to (5) for all ignition events; repeat the calculation of steps (4) to (5) for all weather classes and wind directions; repeat the calculation of steps (1) to (5) for all *LOC*s. The individual risk at the grid point is then calculated by the following formula:

$$IR = \sum_{S} \sum_{M} \sum_{\phi} \sum_{i} \Delta IR_{S,M,\phi,i}$$

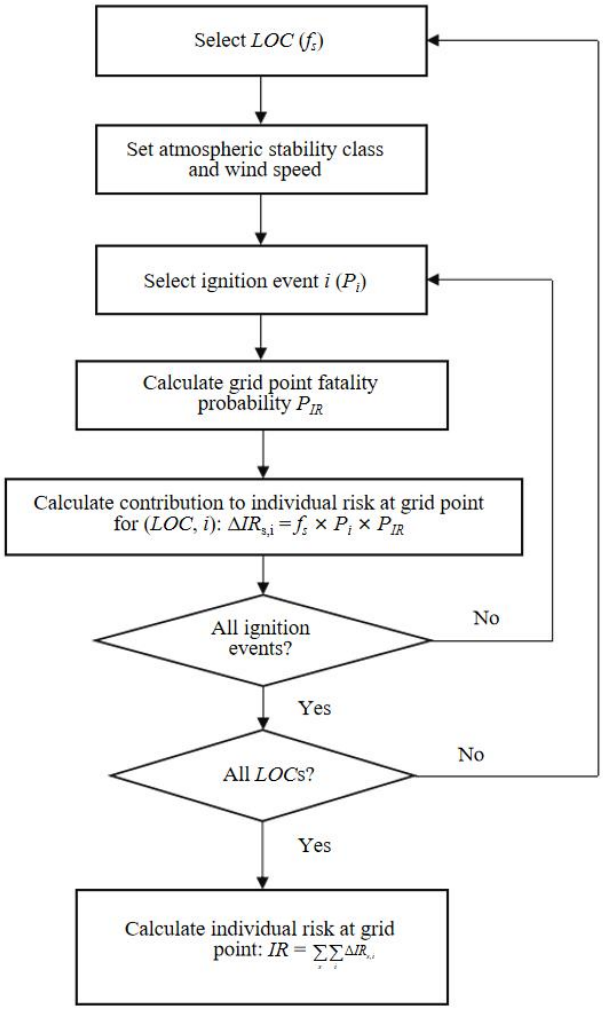


**Figure 6.5.2.1 Individual Risk Calculation Procedure**

### 6.5.3 Calculation of social risk value

6.5.3.1 The societal risk calculation procedure is shown in Figure 6.5.3.1 of this chapter, and the steps are as follows:

(1) Select a leak scenario (*LOC*) and determine the frequency of occurrence $f_S$ of the *LOC*;

(2) Select a weather class $M$, with the probability of $P_M$;

(3) Select a wind direction $\varphi$ under the weather class $M$, with the probability of $P_\varphi$;

(4) For combustible leakage, select an ignition event $i$ and determine the ignition probability $P_i$. Where toxic effects of the substance are considered, the ignition event is not considered

(5) Select a grid cell and determine the number of persons $N_{cell}$ within the grid cell;

(6) Calculate the percentage of deaths $P_{IR}$ within the grid cell under the specific *LOC*, $M$, $\varphi$ and $i$;

(7) Calculate the number of deaths $\Delta N_{S,M,\varphi,i}$ within the grid cell under the specific *LOC*, $M$, $\varphi$ and $i$:

$$\Delta N_{S,M,\varphi,i} = P_{IR} \times N_{cell}$$

(8) Repeat the calculation of steps (5) to (7) for all grid cells, and calculate the total number of deaths $N_{S,M,\varphi,i}$ for *LOC*, *M*, $\varphi$ and *i*;

$$N_{S,M,\varphi,i} = \sum_{\text{all grid cells}} \Delta N_{S,M,\varphi,i}$$

(9) Calculate the combined frequency $f_{S,M,\varphi,i}$ for *LOC*, *M*, $\varphi$ and *i*;

$$f_{S,M,\phi,i} = f_S \times P_M \times P_\phi \times P_i$$

(10) Repeat the calculation of steps (1) to (9) for all *LOC*s ($f_S$), *M*, $\varphi$ and *i*, and construct the F-N curve with the frequency of all accidents with a cumulative total number of deaths $N_{S,M,\varphi,i} \geq N$:

$$F_N = \sum_{S,M,\phi,i} f_{S,M,\phi,i} \rightarrow N_{S,M,\phi,i} \geq N$$

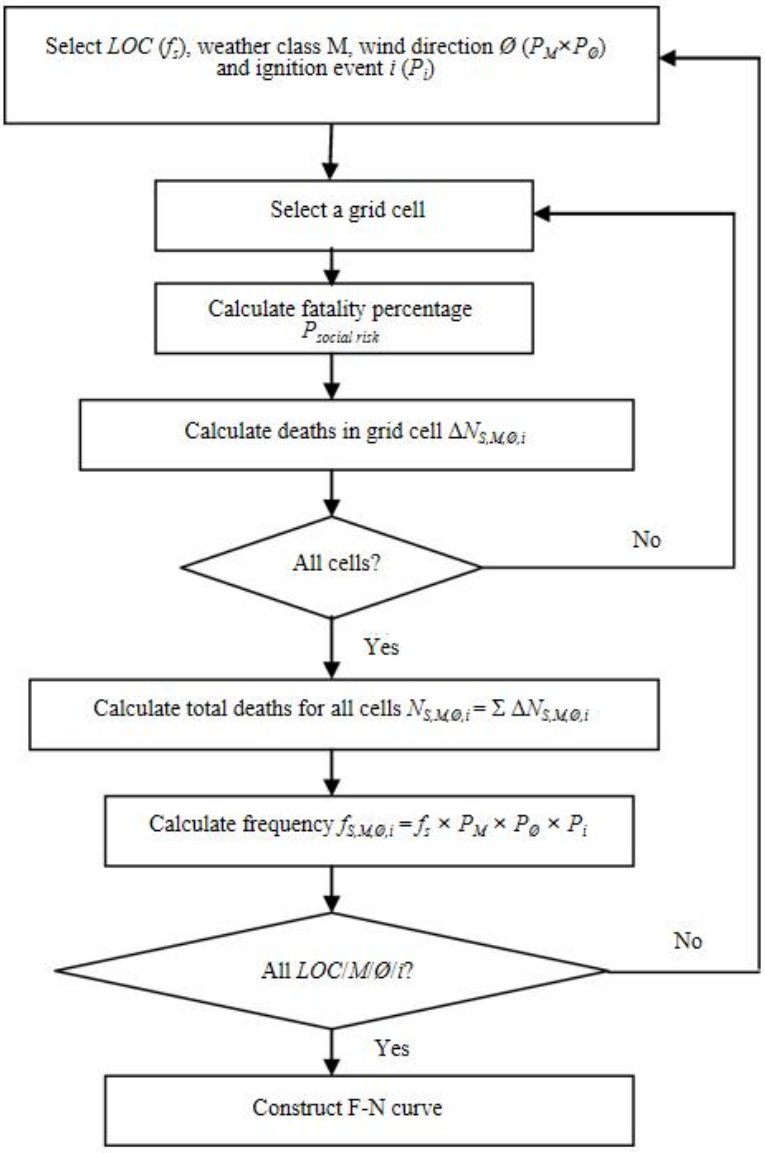


**Figure 6.5.3.1 Societal Risk Calculation Procedure**

### 6.5.4 Risk acceptance criteria

6.5.4.1 General requirements

（1） Risk acceptability criteria represent the overall risk level acceptable within a specified period of time or at a certain stage of behaviour, providing a reference basis for risk analysis and the formulation of risk mitigation measures. Therefore, they are to be presented in advance before the risk assessment is carried out.

（2） Quantitative risk assessment normally uses the ALARP principle to determine risk acceptance criteria, as shown in Figure 6.5.4.1 of this chapter. The ALARP principle divides risk into the following three ranges:

① Unacceptable region: in no way is this risk acceptable except in exceptional circumstances. For the design stage, the design scheme cannot be approved; for existing systems, operations must stop immediately.

② Tolerable region (ALARP region): risk in this region is to be reduced by reasonable and practicable measures as far as possible.

③ Negligible region: risk in this region is acceptable and no measures are required.

（3） Prior to the formal commencement of the risk assessment, the relevant parties are to confirm the acceptance criteria for individual risk or societal risk based on the ALARP principle. Unless otherwise specified, the risk acceptance criteria set out in 6.5.4.2 and 6.5.4.3 of this chapter may be used.

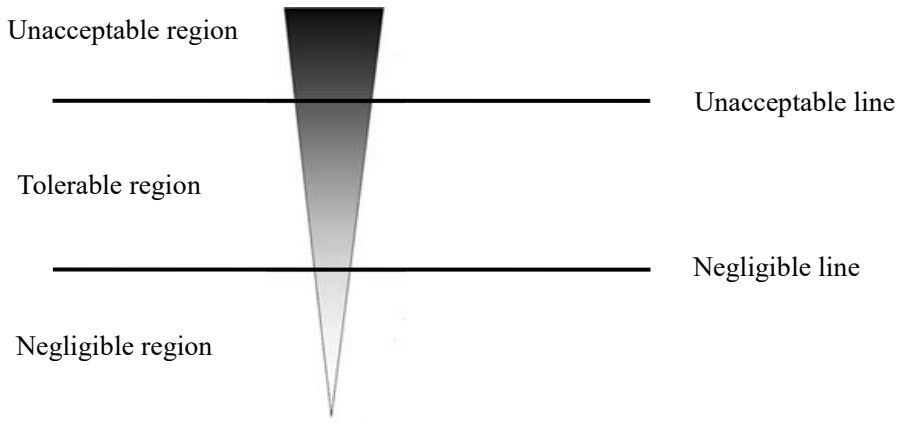


**Figure 6.5.4.1 ALARP Principle**

（4） individual risk assessment is normally to be carried out, and a societal risk assessment is also to be carried out when the project risk involves 10 or more persons.

6.5.4.2 The individual risk acceptance criteria given in Table 6.5.4.2(1), 6.5.4.2(2) or 6.5.4.2(3) of this chapter may be used.

**Individual Risk (IR) Acceptance Criteria⑦** **Table 6.5.4.2 (1)**

| Allowable risk frequency per year | Locations |
|---|---|
| $IR \leq 10^{-5}$ | 1. Locations of bunkering operations (crew, bunkering operators);<br>2. Industrial sites of new development zones (pump rooms, factories). |
| $IR \leq 10^{-6}$ | 1.Residential densely-populated places, such as residential areas, hotels and resorts;<br>2.Public gathering places, such as office places, markets, restaurants and entertainment places. |

⑦From CCS Guidelines for Quantitative Risk Assessment for Oil and Gas.

| | |
|---|---|
| IR≤3x10$^{-7}$ | 1.High-sensitive places, such as schools, hospitals, kindergartens and old people's homes;<br>2.Important targets, such as party and government offices, military restricted zones and culture relic protection sites;<br>3.Special densely-populated areas, such as large stadiums and major transportation hubs. |

**Individual Risk (IR) Acceptance Criteria⑧** **Table 6.5.4.2 (2)**

| Protected objects | Individual risk acceptance criteria (probability values) | |
|---|---|---|
| | New installations (/year) ≤ | In-service installations (/year) ≤ |
| Sparsely-populated spaces (number of persons < 30): single or a small amount of exposed persons. | $1\times10^{-5}$ | $3\times10^{-5}$ |
| Residential densely-populated places (30 persons ≤ number of persons < 100): residential areas, hotels, resorts, etc.<br>Public gathering places (30 persons ≤ number of persons < 100): office places, markets, restaurants, entertainment places, etc. | $3\times10^{-6}$ | $1\times10^{-5}$ |
| High-sensitive places: schools, hospitals, kindergartens, old people's homes, prisons, etc. Important targets: prohibited military zones, military restricted zones, culture relic protection sites, etc.<br>Special densely-populated areas (number of persons ≥ 100): large stadiums, transportation hubs, open-air markets, residential districts, hotels, resorts, office spaces, markets, restaurants, entertainment places. | $3\times10^{-7}$ | $3\times10^{-6}$ |

**Individual Risk (IR) Acceptance Criteria⑨** **Table 6.5.4.2 (3)**

| Protected objects | | Acceptance criteria | |
|---|---|---|---|
| | | Lower limit of ALARP zone | Upper limit of ALARP zone |
| | | Ignorable (generally acceptable) death risk (/year) | Maximum tolerable death risk (/year) |
| IR | Crew | $10^{-6}$ | $10^{-3}$ |
| | Passengers | $10^{-6}$ | $10^{-4}$ |
| | Third parties, public on shore | $10^{-6}$ | $10^{-4}$ |
| | Target values for new ships | $10^{-6}$ | The above values are to be reduced by an order of magnitude. |

6.5.4.3 The societal risk acceptance criteria are to comply with the provisions in Figure 6.5.4.3 of this chapter.

⑧From the Individual and Social Risk Acceptance Criteria for Production and Storage Installations of Dangerous Chemical (For Trial).

⑨ From the Guidelines for Formal Safety Assessment (FSA) (MSC-MEPC.2/Circ.12/Rev.2).

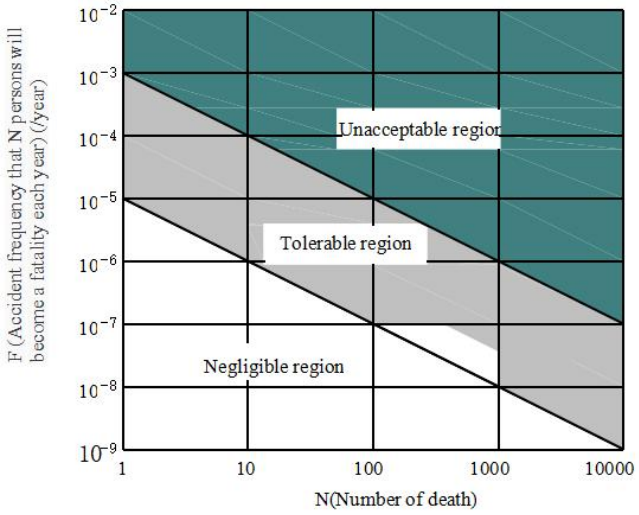


**Figure 6.5.4.3 Societal Risk (SR) Acceptance Criteria**

# Section 6 QRA FOR TYPICAL SCENARIOS

**6.6.1 Dispersion, fire and explosion analysis of hydrogen leakage scenarios in ship hydrogen-related spaces**

6.6.1.1 For hydrogen leakage dispersion analysis of hydrogen-related spaces, the drawings and information required to be collected at least include the ship general arrangement plan, arrangement plan of hydrogen-related spaces, ventilation arrangement plan of hydrogen-related spaces, schematic diagram of the hydrogen system process, list of equipment, piping and fittings of the hydrogen system (including dimensions), etc. Where fire and explosion analysis is to be carried out, the fire protection division arrangement plan of hydrogen-related spaces is also to be provided. For the dispersion, fire and explosion analysis after hydrogen leakage, refer to Appendix 3. Leakage scenarios of hydrogen-related equipment such as valves, piping and the fuel cell itself are to be considered.

6.6.1.2 Where the hazard identification determines that there is a risk of personnel asphyxiation, quantitative analysis of the risk of personnel asphyxiation injury is also to be carried out.

6.6.1.3 The accident scenarios for dispersion, fire and explosion analysis are to consider different hydrogen-related spaces, different dimensions of equipment/piping/fittings and different working pressures of equipment/piping/fittings. The ventilation type and ventilation capacity of the spaces are to be set according to the actual design.

6.6.1.4 The dispersion, fire and explosion analysis of fuel cell spaces is to consider leakage scenarios of fuel cells, piping, valves, filters, pressure transmitters, etc. The dispersion, fire and explosion analysis of hydrogen storage spaces is to consider leakage scenarios of hydrogen storage containers, piping, valves, filters, pressure transmitters, etc.

6.6.1.5 The arrangement of combustible gas detectors and fire detectors within the hydrogen-related spaces can be optimized according to the results of dispersion and fire analysis.

6.6.1.6 The hydrogen leakage duration required for quantitative calculation is to be determined

according to the design of the hydrogen system and its safety monitoring system within the hydrogen-related spaces.

6.6.1.7 Measures are to be taken to reduce the accident risk level according to the results of dispersion, fire and explosion analysis.

# APPENDIX 1 HAZARD IDENTIFICATION WORKSHEETS

## 1.1 HAZID analysis worksheet

Node x：_____

| No. | Guideword | Scenario | Causes | Consequences | Initial risk | | | Existing safeguards | Residual risk | | | Recommendations | Residual risk | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | S | L | R | | S | L | R | | S | L | R | |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |

Note: S — severity of accident consequence; L — likelihood of accident occurrence; R — risk ranking.

## 1.2 HAZOP analysis worksheet

Node x：_____

| No. | Element | Guideword | Deviation | Causes | Consequences | Initial risk | | | Existing safeguards | Residual risk | | | Recommendations | Residual risk | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | S | L | R | | S | L | R | | S | L | R | |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

Note: S — severity of accident consequence; L — likelihood of accident occurrence; R — risk ranking.

## 1.3 FMEA worksheet

| Code | Product or function identification | Function | Failure mode | | Failure cause | Mission phase and operating mode | Failure effect | | | Severity index | Occurrence probability ranking | Risk ranking | Failure detection method | Design improvement | Use compensation measures | Severity index | Occurrence probability ranking | Risk ranking | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ID No. | Mode | | | Local effect | Next higher level effect | Final effect | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |

# APPENDIX 2 Hazard Identification Examples

Part of the contents in the tables is omitted and provided for illustrative purposes only.

## 2.1 Example of HAZID analysis worksheet for fuel cell space

Node 1：Fuel cell space

| No. | Guide word | Causes (accident/event) | Consequences | Existing safeguards | Initial risk | | | Recommendations | Residual risk | | | Responsible person |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | S | L | R | | S | L | R | |
| 1 | Failure of fuel cell module | 1. Abnormal air flow/pressure;<br>2. Abnormal flow of mechanical ventilation system;<br>3. Excessive cooling water inlet temperature;<br>4. Excessive impurities in air and cooling water;<br>5. Failure of system components;<br>6. Internal hydrogen leakage;<br>7. Control system failure | 1. Excessive hydrogen concentration in exhaust gas;<br>2. Undervoltage;<br>3. Insufficient power;<br>4. Blockage of the cooling water pipeline, affecting the cooling effect of the module;<br>5. Affecting the operation of the ship's electric power system | 1. Quick shut-off;<br>2. Multiple fuel cell modules designed and lithium battery pack provided;<br>3.Voltage/current/temperature monitoring and alarm;<br>4. Filter provided in cooling water pipe;<br>5. Product inspection passed | 1 | D | M | 1. Fault test of simulated single module for the first ship | 1 | D | M | |
| 2 | Leakage /rupture | 1.Leakage of hydrogen piping/valves;<br>2. Seal failure of fuel cell module;<br>3. Manufacturing defects;<br>4. Human factors/improper operation | 1. Affecting the operation of the ship's electric power system;<br>2. May lead to fire and explosion | 1. Hydrogen detectors;<br>2. Safe operating procedures;<br>3. Product inspection passed;<br>4. Two independent fuel cell spaces are provided;<br>5. Mechanical ventilation provided in the space;<br>6. Interlock for fuel supply shut-off;<br>7. Double-wall pipe for gas supply line; | 2 | C | M | 1.It is recommended that the ventilation be designed with air supply from the lower part and exhaust from the upper part;<br>2.Strengthen personnel operational skill training and establish relevant operating procedures | 2 | C | M | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 8. Gas-tight design of fuel cell module | | | | | | | | |
| 3 | Fire/explosion | 1. External fire;<br>2. Leaked hydrogen ignited by ignition source (fuel cell);<br>3. Human factors/improper operation | 1. Equipment damage;<br>2. Personal casualties;<br>3. Operation of the ship's electric power system affected | 1. Fire detection;<br>2. Space strength sufficient to withstand the effect of explosion overpressure;<br>3. A60 fire protection division;<br>4. Stationary fuel cell design standard adopted, satisfying the environmental conditions for operation in the space;<br>5. IMO requirements for fuel cell spaces satisfied;<br>6. CO2 fire-extinguishing system provided | 3 | B | M | 1. Numerical simulation of local explosion of fuel cell module;<br>2. Full evaluation of fire handling method;<br>3. Personnel training and emergency plans;<br>4. Consideration of explosion-proof pressure relief measures for fuel cell space | 3 | B | M | |

## 2.2 Example of HAZID analysis worksheet for berthing and mooring stage

Node 1：Berthing and mooring stage

| No. | Guide-word | Scenario | Causes | Consequences | Existing safeguards | Initial risk | | | Recommendations | Residual risk | | | Responsible person |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | S | L | R | | S | L | R | |
| 1 | Failure of mooring lines | Failure of mooring lines between the ship and the jetty | 1. Failure of mooring winch;<br>2. Damage to mooring posts;<br>3. Improper selection of mooring line type;<br>4. Improper mooring arrangement;<br>5. Improper mooring operation;<br>6. Severe weather | 1. Relatively large movement or drift of the ship, causing structural damage to the receiving ship/bunkering ship;<br>2. Affecting hydrogen bunkering operations;<br>3. Personal injury | 1. Spare mooring lines provided on board;<br>2. Routine inspection and maintenance of mooring winches, mooring posts and mooring lines | 3 | A | L | 1.Close attention to local weather forecasts; berthing and mooring operations to be carried out under permissible operating conditions;<br>2.Assessment of the reliability of the mooring arrangement | 3 | A | L | |

| No. | Guide-word | Scenario | Causes | Consequences | Existing safeguards | Initial risk | | | Recommendations | Residual risk | | | Responsible person |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | S | L | R | | S | L | R | |
| 2 | Collisi-on | Collision between the ship and the jetty | 1.Insufficient manoeuvring control;<br>2.Failure of the ship to come alongside the jetty fenders;<br>3. Severe weather | 1. Damage to ship structure;<br>2. Damage to jetty equipment;<br>3. Personal injury | 1. Fenders provided on the jetty | 3 | B | M | 1. Close attention to local weather forecasts; berthing operations to be carried out under permissible operating conditions;<br>2. Strengthening of practical training and examination for crew;<br>3. Strengthening of tracking and early warning of severe hydrological and meteorological information | 3 | A | L | |

## 2.3 Example of HAZOP analysis worksheet for high-pressure hydrogen supply and bunkering

Node 1：High-pressure hydrogen supply

| No. | Element | Guide word | Deviation | Causes | Consequences | Existing safeguarding | Initial risk | | | Recommendations | Residual risk | | | Responsible person |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | S | L | R | | S | L | R | |
| 1 | Flow | No | No flow from hydrogen cylinder bundle to pressure reducing valve assembly | 1. Valve failure and closure | 1. Failure to supply gas | 1. Two sets of gas supply lines are provided | 1 | B | L | | 1 | B | L | |
| 2 | | Less | Low flow from hydrogen cylinder bundle to pressure reducing valve | 1. Failure of pressure reducing valve;<br>2. Sensor failure;<br>3. Low pressure in hydrogen cylinders;<br>4. Filter blockage | 1. Reduced gas supply, affecting the cruising range | None | 1 | B | L | 1. Periodic cleaning or replacement of filter | 1 | B | L | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | assembly | | | | | | | | | | | |
| 3 | | More | High flow from hydrogen cylinder bundle to pressure reducing valve assembly | 1. Sensor failure;<br>2. Hydrogen leakage;<br>3. Hydrogen venting | 1. Hydrogen leakage; 2. Large amount of hydrogen released; 3. Failure to supply gas normally | 1. Relief valve provided in the line and connected to the hydrogen vent header;<br>2. Flame arrester provided in the hydrogen vent header;<br>3. Combustible gas detection and alarm;<br>4. Excess flow valve provided at hydrogen cylinder outlet;<br>5. Flow limiting valve provided at hydrogen cylinder outlet | 3 | B | M | 1. Additional flow limiting valve to be provided on the high-pressure gas supply header of each cylinder bundle | 3 | B | M | |
| 4 | Pressure | No | No pressure from hydrogen cylinder bundle to pressure reducing valve assembly | 1. Valve failure and closure | 1. Failure to supply gas | 1. Two sets of gas supply lines are provided | 1 | B | L | | 1 | B | L | |
| 5 | | Less | Low pressure from hydrogen cylinder bundle to pressure reducing valve assembly | 1. Failure and opening of valve in the vent line;<br>2. Sensor failure;<br>3. Low pressure in hydrogen cylinders;<br>4. Filter blockage | 1. Reduced gas supply, affecting the cruising range | 1. Pressure gauge provided | 1 | B | L | | 1 | B | L | |
| 6 | Tempera-ture | Less | Low temperature from | 1. Rapid venting of hydrogen | 1. Frost formation in the pipeline | None | 1 | C | L | | 1 | C | L | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | hydrogen cylinder bundle to pressure reducing valve assembly | | | | | | | | | | | |
| 7 | | More | High temperature from hydrogen cylinder bundle to pressure reducing valve assembly | 1. High temperature of hydrogen source in the cylinders | 1. Affecting the efficiency of the fuel cell | 1. Temperature sensors are provided in the cylinders;<br>2. Thermally activated pressure relief device (TPRD) is provided at cylinder outlet | 1 | B | L | | 1 | B | L | |

Node 2：High-pressure hydrogen bunkering

| No. | Element | Guide word | Deviation | Causes | Consequences | Existing safeguarding | Initial risk | | | Recommendations | Residual risk | | | Responsible person |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | S | L | R | | S | L | R | |
| 1 | Flow | No | No flow from bunkering station to hydrogen cylinder bundle | 1. Valve failure and closure;<br>2. Failure of cylinder outlet combination valve;<br>3. Failure of hydrogen dispenser | 1. Failure to bunker;<br>2. Overpressure of bunkering hose | 1. Low pressure alarm of hydrogen dispenser;<br>2. Relief valve provided in the bunkering line | 1 | B | L | | 1 | B | L | |
| 2 | | Less | Low flow from bunkering station to hydrogen | 1. Internal leakage of vent fittings/valves;<br>2. Sensor failure;<br>3. Compressor failure; | 1. Extended bunkering time | 1. Pressure monitoring provided in bunkering line and hydrogen cylinders;<br>2. Combustible gas detection provided in | 1 | B | L | 1. Pressure gauges PG-01/02-01 to be relocated upstream of the filter;<br>2. Periodic maintenance of filter | 1 | B | L | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | cylinder bundle | 4. High pressure in hydrogen cylinders;<br>5. Filter blockage | | bunkering station and hydrogen cylinder storage room;<br>3. Flow meter provided in hydrogen dispenser | | | | | | | | |
| 3 | | More | High flow from bunkering station to hydrogen cylinder bundle | 1. Sensor failure;<br>2. During balanced bunkering, abnormal opening of downstream valves | 1. Overpressure of pipeline;<br>2. Large amount of hydrogen released | 1. Relief valve provided in the line and connected to the hydrogen vent header;<br>2. High pressure alarm;<br>3. Thermally activated pressure relief device (TPRD) provided on hydrogen storage cylinders;<br>4. Flame arrester provided in the hydrogen vent header | 2 | B | L | 1. Pre-bunkering checklist | 2 | B | L | |
| 4 | | Reverse | Reverse flow from bunkering station to hydrogen cylinder bundle | 1. Rupture of compressor piping | 1. Backflow and leakage of high-pressure hydrogen | Check valve provided at compressor end; 2. Check valve provided in hydrogen bunkering line | 2 | A | L | | 2 | A | L | |
| 5 | Pressure | No | No pressure from bunkering station to hydrogen cylinder bundle | 1.Valve failure and closure;<br>2.Failure of cylinder outlet combination valve;<br>3. Failure of hydrogen dispenser | 1. Failure to bunker;<br>2. Overpressure of bunkering hose | 1. Low pressure alarm of hydrogen dispenser;<br>2. Relief valve provided in the bunkering line | 1 | B | L | | 1 | B | L | |
| 6 | | Less | Low pressure from bunkering station to hydrogen cylinder bundle | 1. Internal leakage of vent fittings/valves;<br>2. Sensor failure;<br>3. Compressor failure;<br>4. Filter blockage | 1. Extended bunkering time | 1. Pressure monitoring provided in bunkering line and hydrogen cylinders;<br>2. Combustible gas detection provided in bunkering station and hydrogen cylinder storage | 1 | B | L | 1. PG-01/02-01 to be relocated upstream of the filter;<br>2. Periodic maintenance of filter | 1 | B | L | |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | room | | | | | | | | | |
| 7 | | More | Excessive pressure from bunkering station to hydrogen cylinder bundle | 1. Sensor failure;<br>2. Filter blockage;<br>3. Excessive bunkering temperature | 1. Overpressure of pipeline;<br>2. Large amount of hydrogen released | 1. Relief valve provided in the line and connected to the hydrogen vent header;<br>2. High pressure alarm;<br>3. Pressure relief device provided on hydrogen storage cylinders; 4. Flame arrester provided in the hydrogen vent header | 2 | B | L | | 2 | B | L | |
| 8 | | Fluctuation | Pressure fluctuation from bunkering station to hydrogen cylinder bundle | 1. Compressor failure | 1. Possible severe vibration of the bunkering line, affecting the securing of the bunkering hose;<br>2. Impact on instruments | 1. Bunkering hose sufficiently secured | 1 | C | L | 1. Buffer tank to be provided downstream of the compressor | 1 | C | L | |
| 9 | Temperature | More | Excessive temperature from bunkering station to hydrogen cylinder bundle | 1. Excessive bunkering rate;<br>2. Excessive ambient temperature | 1. Insufficient bunkering quantity;<br>2. Release of pressure relief device;<br>3. Possible failure of fuel cell start-up (the valve upstream of the fuel cell may not withstand high temperature);<br>4. Long-duration high temperature may cause damage to the carbon fibre material of the hydrogen cylinders, affecting service life | 1. Pressure relief device provided on hydrogen storage cylinders;<br>2. Temperature monitoring of hydrogen cylinders;<br>3. Flow monitoring of hydrogen dispenser | 2 | C | M | 1. Consideration of additional cooler on the hydrogen bunkering station side;<br>2. Determination of appropriate bunkering rate | 2 | B | L | |

## 2.4 FMEA example of low-temperature proton exchange membrane fuel cell

2.4.1 Indenture level diagram of low-temperature proton exchange membrane fuel cell

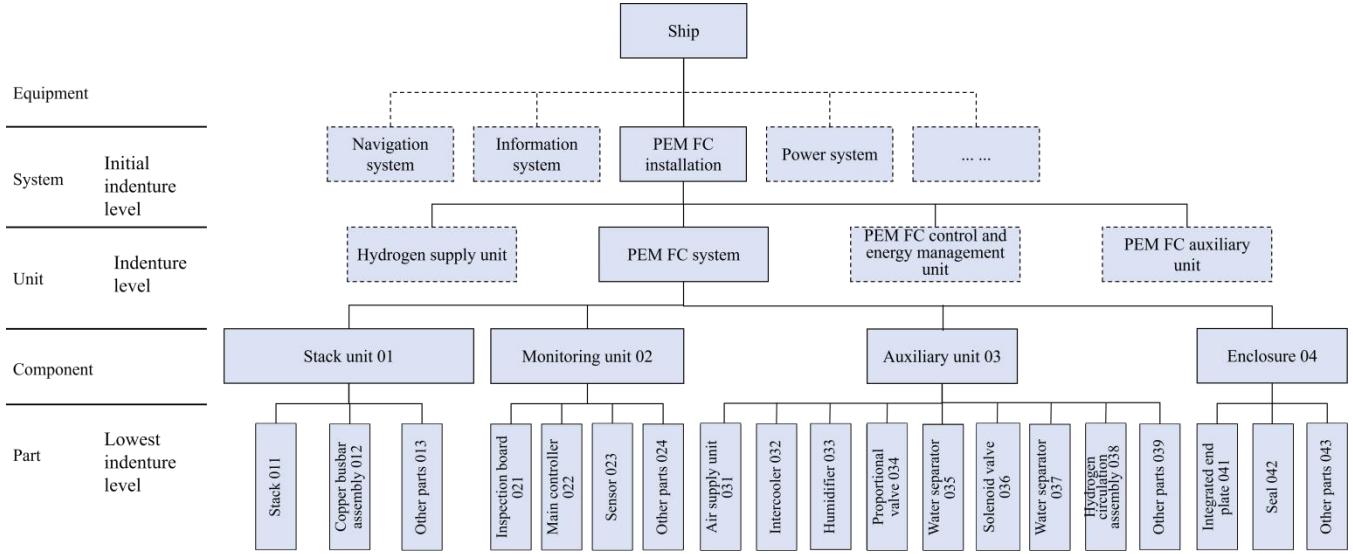


**Figure 2.4.1 Indenture Level Diagram of Low-temperature Proton Exchange Membrane Fuel cell**

2.4.2 Functional block diagram of proton exchange membrane fuel cell

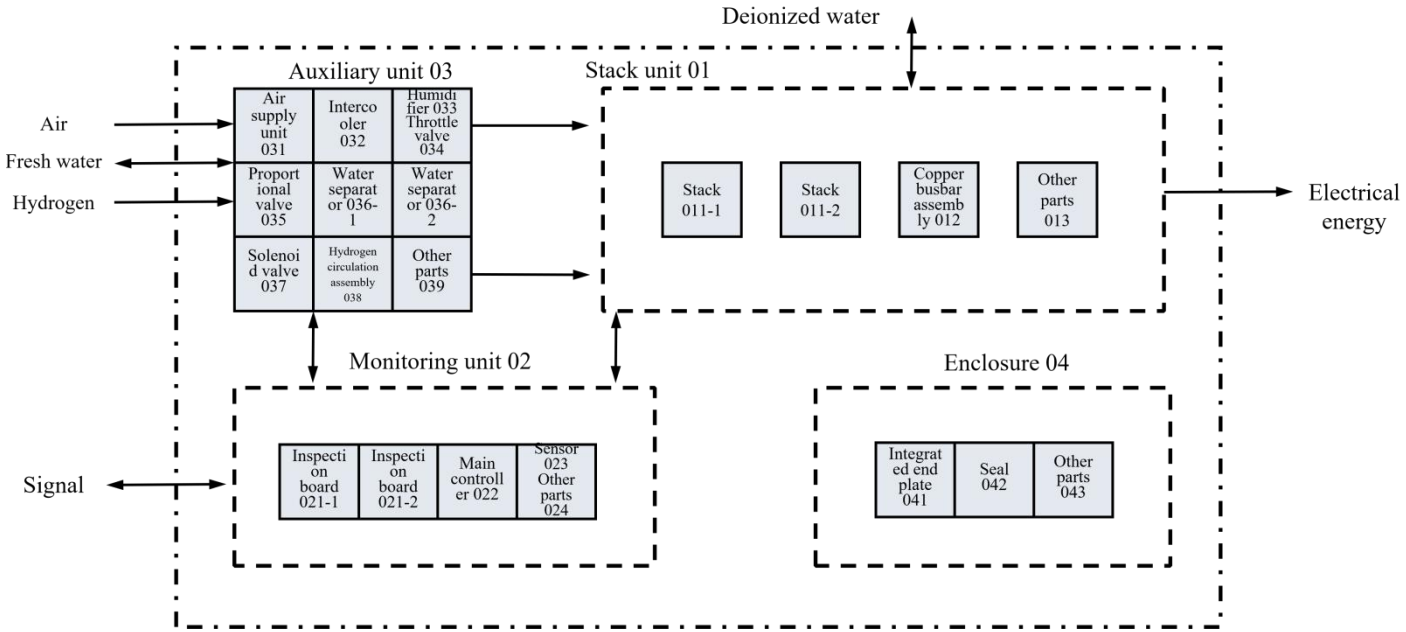


**Figure 2.4.2 Functional Block Diagram of Proton Exchange Membrane Fuel Cell**

2.4.3 Reliability block diagram of proton exchange membrane fuel cell

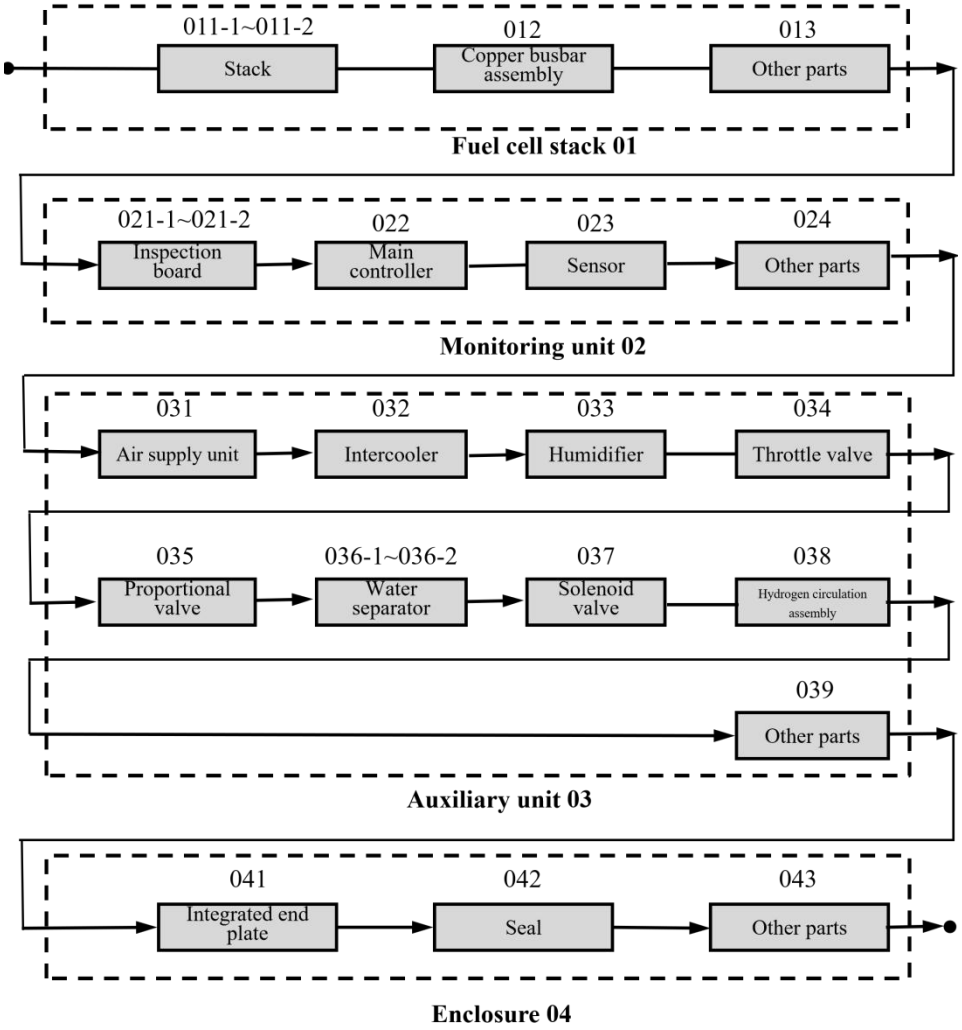


**Figure 2.4.3 Basic Reliability Block Diagram of Proton Exchange Membrane Fuel Cell**

2.4.4 Example of FMEA worksheet for low-temperature proton exchange membrane fuel cell

| Code | Product or function identification | Function | Failure mode | | Failure cause | Mission phase and operating mode | Failure effect | | | Severity index | Occurrence probability ranking | Risk ranking | Failure detection method | Design improvement | Use compensation measures | Severity index | Occurrence probability ranking | Risk ranking | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ID No. | Mode | | | Local effect | Next higher level effect | Final effect | | | | | | | | | | |
| 011 | Fuel cell stack | Hydrogen-oxygen reaction and output of electrical energy | 0111 | Low single-cell voltage | Insufficient gas supply or internal flooding of the stack | Operating stage | Reduction of single-cell service life | System load reduction | Fuel cell system starts standby system or increases battery output | 1 | 2 | 3 | Comparison of adjacent cell voltages | Optimisation of cell water management | Load reduction operation set | 1 | 1 | 2 | |
| | | | 0112 | Hydrogen-air crossover | Pinholes or cracking of membrane electrode assembly | Operating stage | Loss of stack function | System shutdown | System repair | 2 | 2 | 4 | Sensor detection | Enhancement of membrane electrode assembly strength or optimisation of assembly process | Additional membrane electrode assembly strength test and crossover test | 1 | 1 | 2 | |
| | | | 0113 | Leakage | Seal ageing failure or insufficient assembly force | Operating stage | Leakage of reactant gas or cooling water | System shutdown | System repair | 2 | 2 | 4 | External leakage detection using nitrogen | Optimisation of seal design and assembly strength | Appropriate tightening of fastening nuts | 2 | 1 | 3 | |
| | | | 0114 | High temperatu-re | Insufficient cooling water flow or failure of heat dissipation device | Operating stage | High temperatu-re damage to the stack | System shutdown | System repair | 2 | 2 | 4 | Sensor detection | Optimisation of control strategy | Shutdown protection set | 1 | 1 | 2 | |
| | | | 0115 | Over- | Overload or | Operating | Cell | System | System | 2 | 2 | 4 | Sensor | Optimisation of | Shutdown | 1 | 1 | 2 | |

| Code | Product or function identification | Function | Failure mode | | Failure cause | Mission phase and operating mode | Failure effect | | | Severity index | Occurrence probability ranking | Risk ranking | Failure detection method | Design improvement | Use compensation measures | Severity index | Occurrence probability ranking | Risk ranking | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ID No. | Mode | | | Local effect | Next higher level effect | Final effect | | | | | | | | | | |
| | | | | current | short circuit | stage | reversal of the stack | shutdown | repair | | | | detection | control strategy | protection set | | | | |
| 012 | Copp -er bar assem -bly | Current circuit | 0121 | Insufficie -nt insulation | Insulation ageing | Operating stage | Electric leakage | System shutdown | System repair | 2 | 2 | 4 | Sensor measurement | Optimisation of insulation design | Advance maintenance | 2 | 1 | 3 | |

## 2.5 FMEA example of solid oxide fuel cell

2.5.1 Indenture level diagram of solid oxide fuel cell

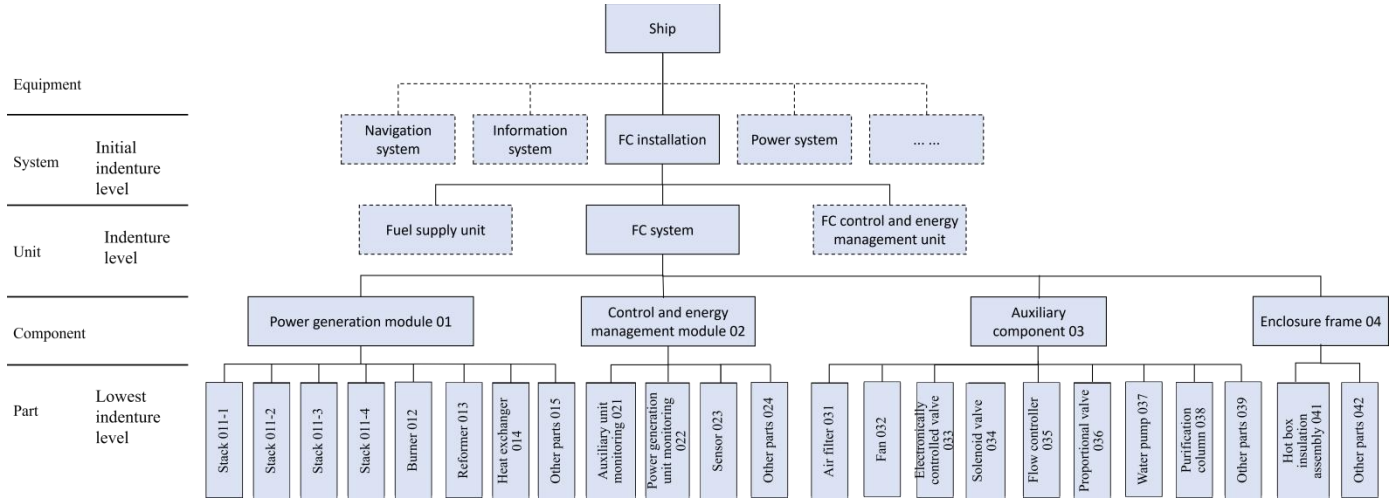


**Figure 2.5.1 Indenture Level Diagram of Solid Oxide Fuel Cell**

2.5.2 Functional block diagram of solid oxide fuel cell

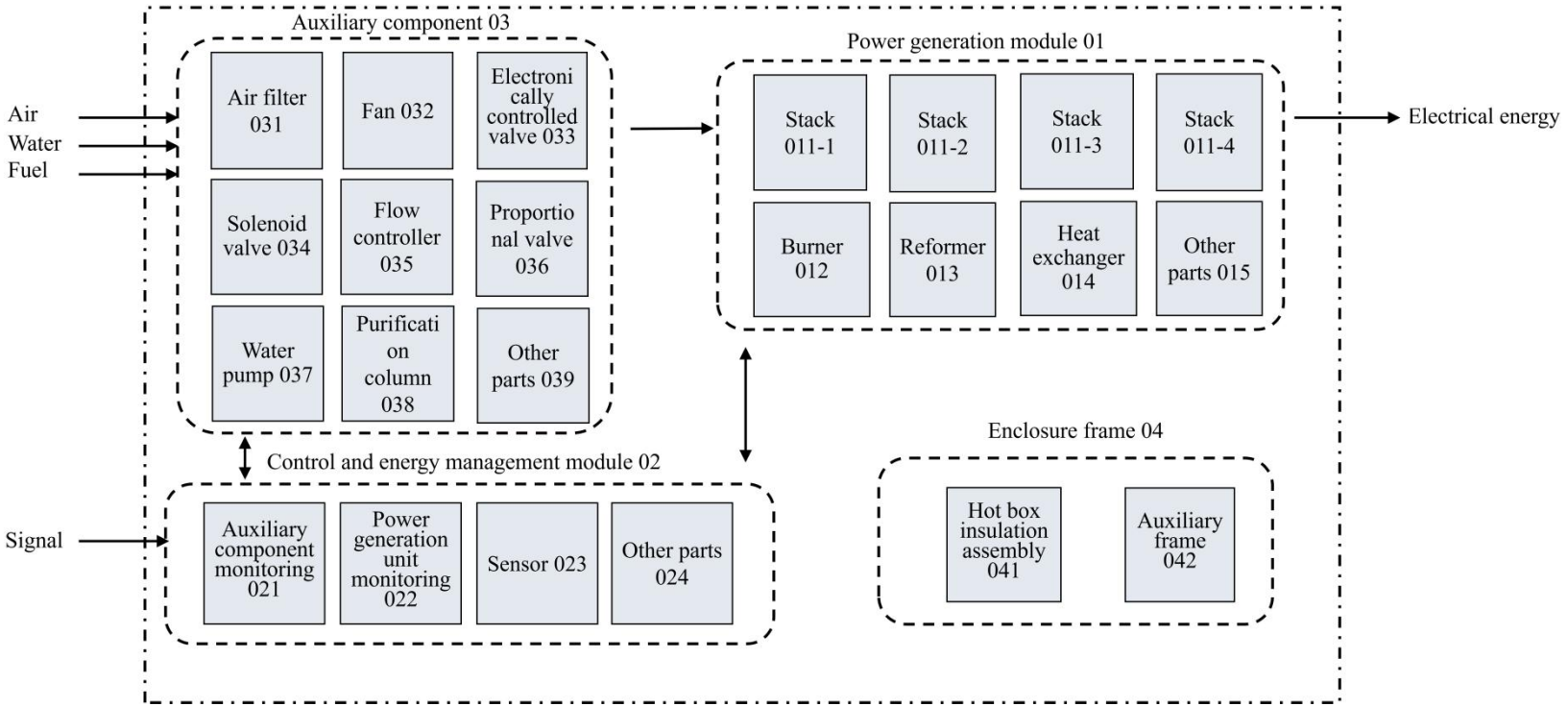


**Figure 2.5.2 Functional Block Diagram of Solid Oxide Fuel Cell**

2.5.3 Reliability block diagram of solid oxide fuel cell

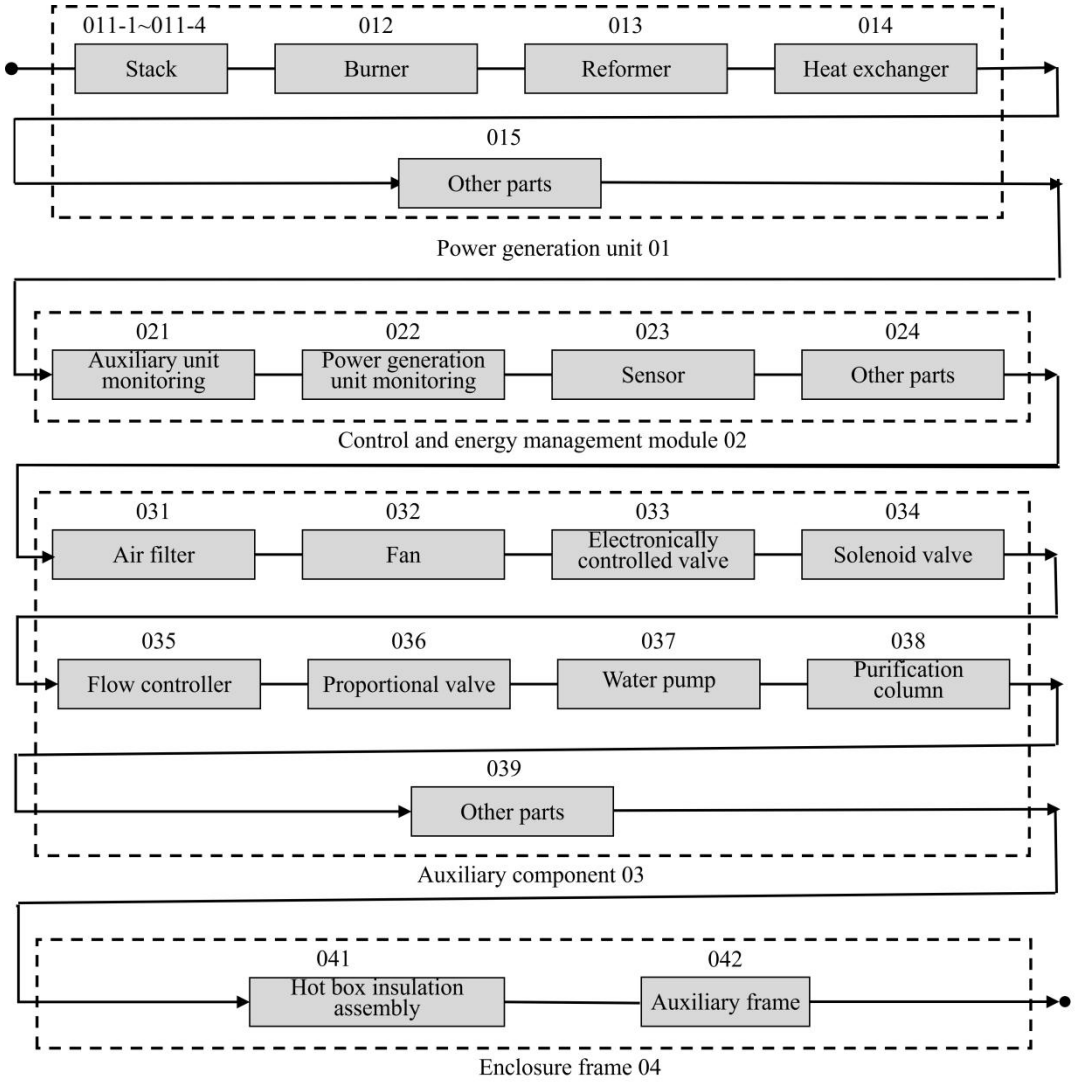


**Figure 2.5.3 Basic Reliability Block Diagram of Solid Oxide Fuel Cell**

2.5.4 Example of FMEA worksheet for solid oxide fuel cell

| Code | Product or function identification | Function | Failure mode | | Failure cause | Mission phase and operating mode | Failure effect | | | Severity index | Occurrence probability ranking | Risk ranking | Failure detection method | Design improvement | Use compensation measures | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ID No. | Mode | | | Local effect | Next higher level effect | Final effect | | | | | | | |
| 011 | Fuel cell stack | Fuel gas and air reaction and output of electrical energy | 0111 | Failure to reach hot standby state | Leakage of stack | Operating stage | Power generation performance of stack | System shutdown | System repair | 3 | 2 | 4 | Online voltage detection | Optimisation of control strategy | Shutdown protection set | |
| | | | 0112 | Initial power cannot be loaded to rated value | Stack degradation | Operating stage | Power generation performance of stack | System load reduction | System repair | 3 | 2 | 4 | Online voltage detection | Optimisation of control strategy | Shutdown protection set | |
| | | | 0113 | Excessive leakage | Seal ageing failure | All mission stages | Fuel gas leakage | System shutdown | System repair | 3 | 2 | 4 | External leakage detection using nitrogen | Optimisation of seal design | Shutdown protection set | |
| 012 | Burner | Consumpti-on of tail gas from the stack and provision | 0121 | Failure to start | Communicat ion failure, breakage of ion rods or transformer failure | All mission stages | Failure to start the stack module | System shutdown | System repair | 3 | 2 | 4 | Power-on self-check | Selection of high-reliability components | Shutdown protection set | |

| Code | Product or function identification | Function | Failure mode | | Failure cause | Mission phase and operating mode | Failure effect | | | Severity index | Occurrence probability ranking | Risk ranking | Failure detection method | Design improvement | Use compensation measures | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ID No. | Mode | | | Local effect | Next higher level effect | Final effect | | | | | | | |
| | | of heat | 0122 | Burner over-temperatu-re | Excessive fuel gas quantity; insufficient air quantity | All mission stages | | System shutdown | System repair | 4 | 2 | 4 | Online temperature detection | Optimisation of control strategy | Shutdown protection set | |
| 013 | Reformer | Fuel reforming and conversion | 0131 | Reduction in reforming efficiency | Carbon deposition in reformer or ageing of reforming catalyst | All mission stages | Degradation of stack module performance | System load reduction | System repair | 4 | 2 | 4 | Online pressure detection | Selection of high-reliability components | Load reduction operation set | |

## 2.6 FMEA example of electric power system under navigation scenarios

2.6.1 Indenture level diagram of electric power system under navigation scenarios

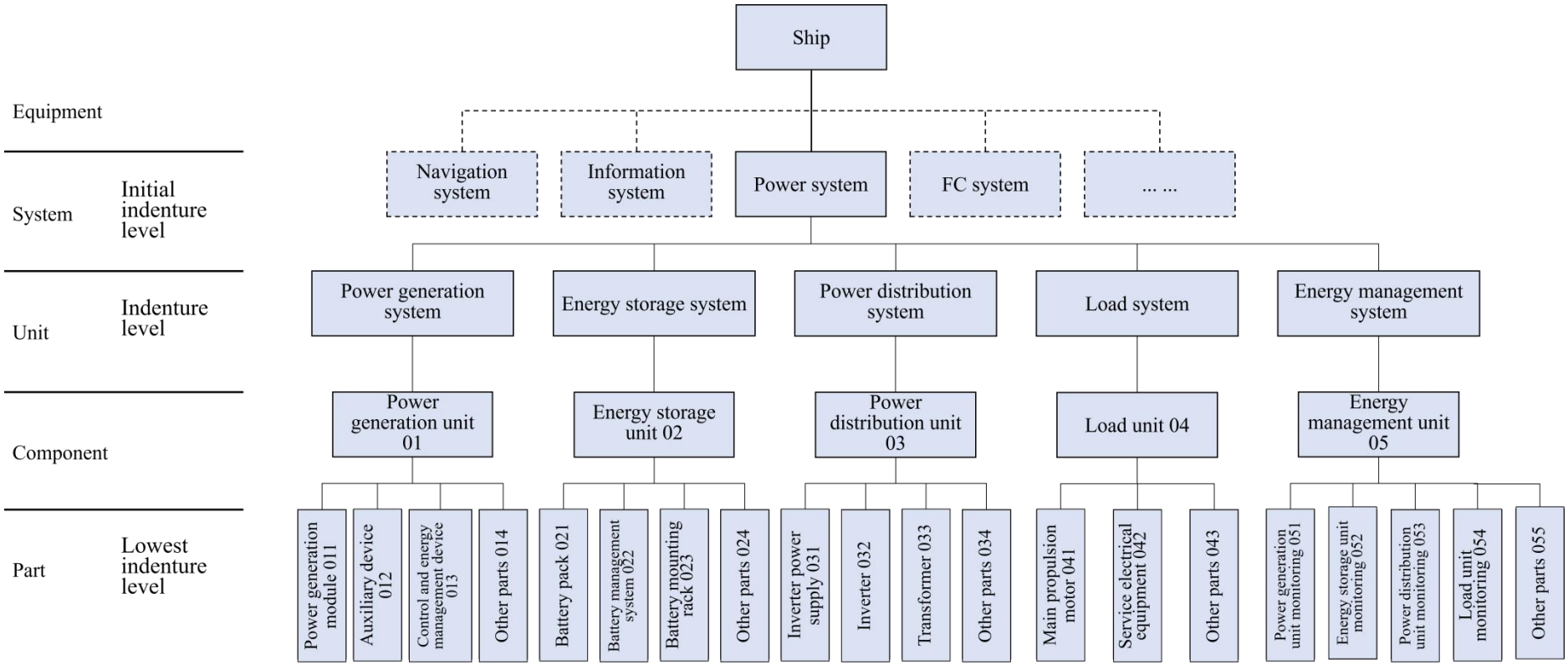


**Figure 2.6.1 Indenture Level Diagram of Electric Power System Under Navigation Scenarios**

2.6.2 Function block diagram of electric power system under navigation scenarios

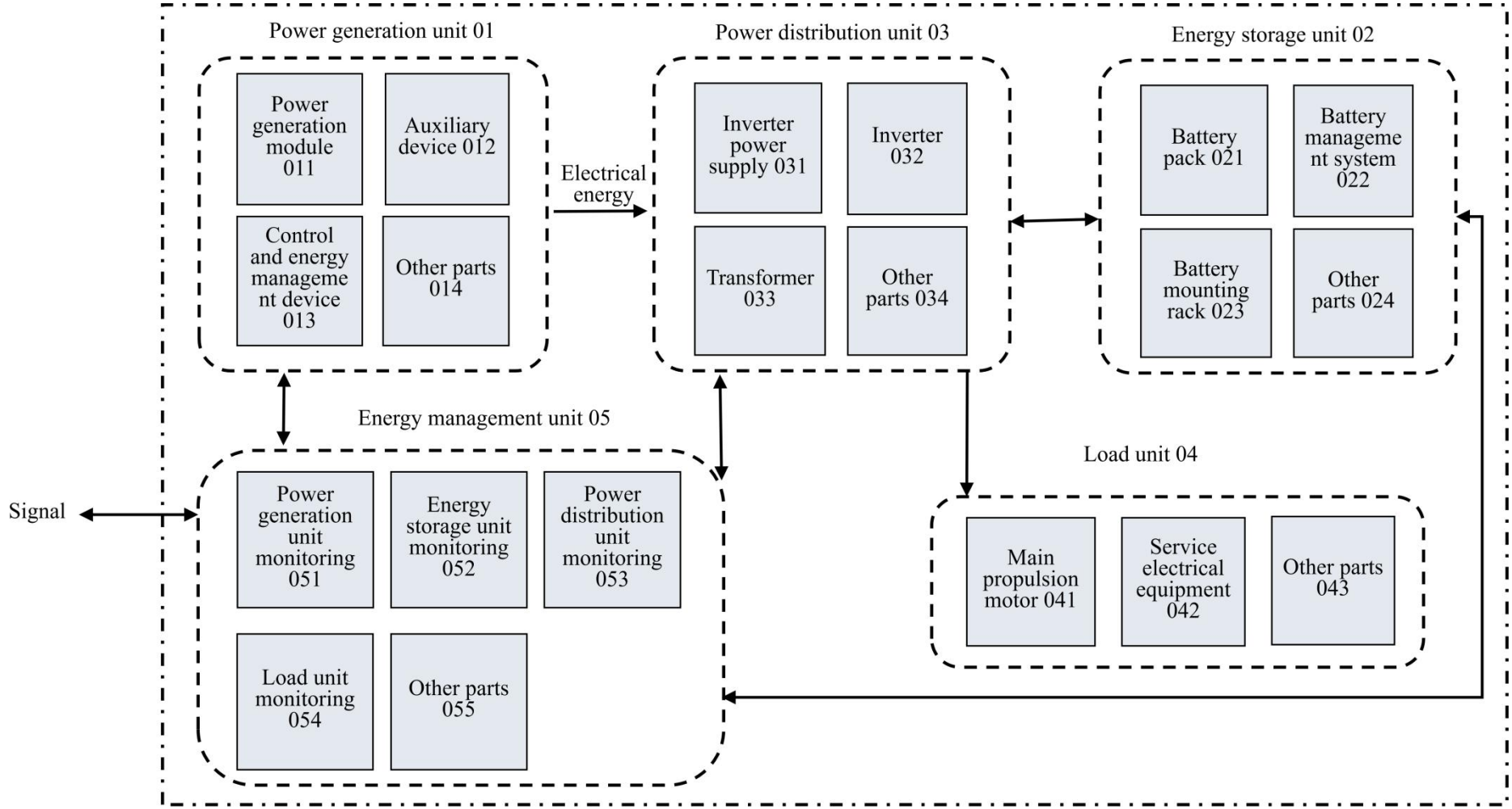


**Figure 2.6.2 Functional Block Diagram of Electric Power System under Navigation Scenarios**

2.6.3 Reliability block diagram of electric power system under navigation scenarios

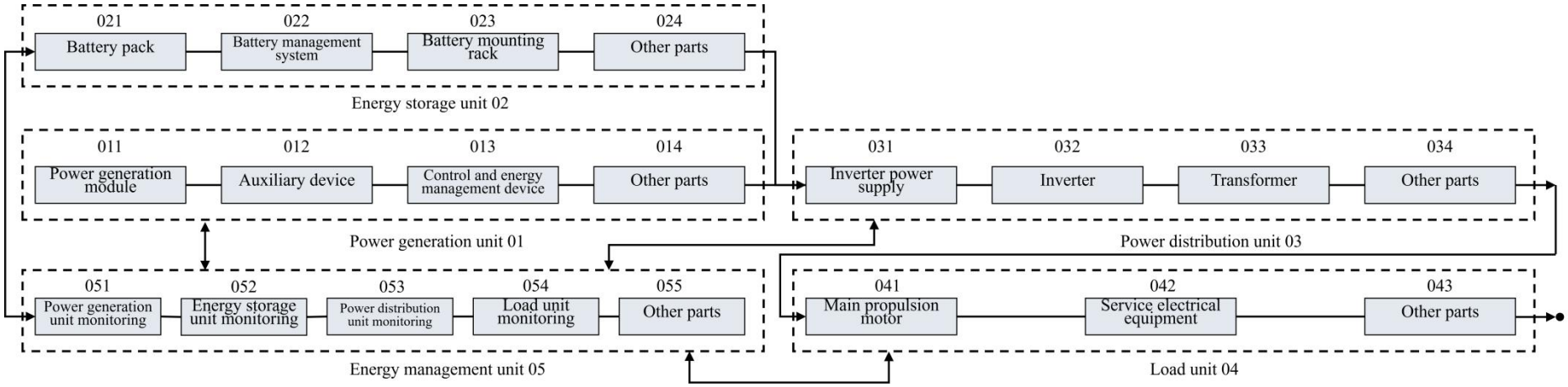


**Figure 2.6.3 Basic Reliability Block Diagram of Electric Power System under Navigation Scenarios**

2.6.4 Example of FMEA worksheet for electric power system under navigation scenarios

| Code | Product or function identification | Function | Failure mode | | Failure cause | Mission phase and operating mode | Failure effect | | | Severity index | Occurrence probability ranking | Risk ranking | Failure detection method | Design improvement | Use compensation measures | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ID No. | Mode | | | Local effect | Next higher level effect | Final effect | | | | | | | |
| 011 | Power generation module | Fuel gas and air reaction and output of electrical | 0111 | Failure to reach hot standby state | Leakage of power generation module | Operating stage | Power generation performance of power generation module | System shutdown, failure to supply electrical energy | System repair | 3 | 2 | 4 | Online voltage detection | Optimisation of control strategy | 1.Shutdown protection set; 2.Power supply via the energy storage system | |

| Code | Product or function identification | Function | Failure mode | | Failure cause | Mission phase and operating mode | Failure effect | | | Severity index | Occurrence probability ranking | Risk ranking | Failure detection method | Design improvement | Use compensation measures | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ID No. | Mode | | | Local effect | Next higher level effect | Final effect | | | | | | | |
| | | energy | 0112 | Initial power cannot be loaded to rated value | Degradation of power generation module | Operating stage | Power generation performance of power generation module | System load shedding, failure to supply electrical energy | System repair | 3 | 2 | 4 | Online voltage detection | Optimisation of control strategy | 1.Shutdown protection set; 2.Power supply via the energy storage system | |
| | | | 0113 | Excessive leakage | Seal ageing failure | All mission stages | Fuel gas leakage | System shutdown, failure to supply electrical energy | System repair | 3 | 2 | 4 | External leakage detection using nitrogen | Optimisation of seal design | 1.Shutdown protection set; 2.Power supply via the energy storage system | |
| 012 | Auxiliary devices | Provision and maintenance of necessary working conditions and environment for the power generation module | 0121 | Failure of key equipment functions | Failure of key equipment such as fans, valves and pumps | All mission stages | Failure of power generation module | System shutdown, failure to supply electrical energy | System repair | 3 | 2 | 4 | 1.Monitoring of component fault codes; 2.sensor monitoring | Selection of high-reliability components | 1.Shutdown protection set; 2.Power supply via the energy storage system | |

| Code | Product or function identification | Function | Failure mode | | Failure cause | Mission phase and operating mode | Failure effect | | | Severity index | Occurrence probability ranking | Risk ranking | Failure detection method | Design improvement | Use compensation measures | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ID No. | Mode | | | Local effect | Next higher level effect | Final effect | | | | | | | |
| 013 | Control and energy management device | Control of the operation of the entire system and management of the output of electrical energy | 0131 | Communication failure | Broken wire, loosening | All mission stages | Interruption of data transmission | System shutdown, failure to supply electrical energy | System repair | 3 | 2 | 4 | Communication monitoring | Optimisation of wiring workmanship | 1.Shutdown protection set; 2.Power supply via the energy storage system | |
| | | | 0132 | Control failure | Broken wire; component failure | All mission stages | Control failure | System shutdown, failure to supply electrical energy | System repair | 3 | 2 | 4 | Comparison of control commands and actuator responses | Optimisation of control strategy | 1.Shutdown protection set; 2.Power supply via the energy storage system | |

# APPENDIX 3 EXAMPLES ANALYSIS OF HYDROGEN LEAKAGE DISPERSION, FIRE AND EXPLOSION IN HYDROGEN-RELATED SPACES

This example is provided only to demonstrate the analysis method. Actual calculations are to be carried out in conjunction with the actual design of the ship and possible accident scenarios.

### 3.1 Example of hydrogen leakage dispersion analysis

(1)Ventilation arrangement

The ventilation inlet, ventilation outlet, ventilation type and ventilation rate are determined according to the actual design.

(2)Accident consequence simulation and analysis

A leakage of high-pressure hydrogen (40 MPa) through a circular hole of 10 mm in diameter is selected as the typical scenario, with the leakage point located at the connection joint between the hydrogen cylinder and the hydrogen supply line. The combustible vapour clouds at different times after the occurrence of leakage are shown in Figures 3.1-1 and Figure 3.1-2 of this Appendix. The combustible vapour cloud fills the entire hydrogen storage space within 3.4 seconds. The net volume of the space is 95 m³.

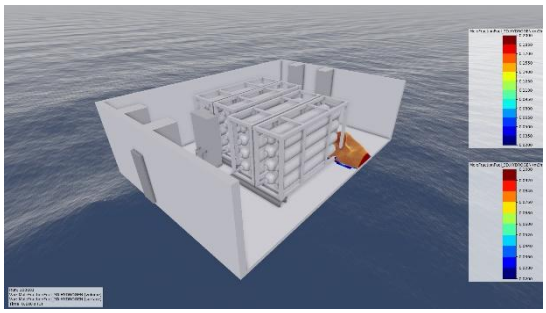

**Figure 3.1-1 Combustible Vapour Cloud at 0.1 s (2%–20%)**

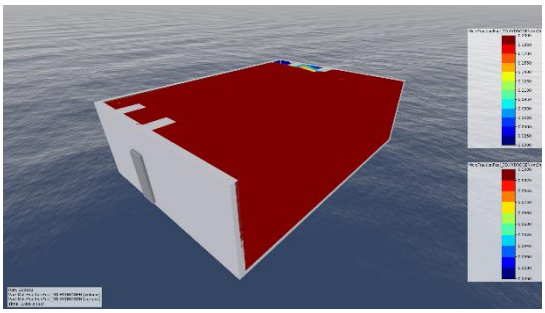

**Figure 3.1-2 Combustible Vapour Cloud at 3 s (2%–20%)**

(3)Dispersion consequence analysis

Based on the simulation of all identified hydrogen dispersion accident scenarios, the consequence analysis of different hydrogen leakage dispersion events in the hydrogen storage space is shown in Table 3.1of this Appendix.

**Table 3.1 Quantitative Data of Leakage and Dispersion Consequences in the Hydrogen Storage Space**

| Leakage aperture (mm) | Pressure (MPa) | Volume of combustible gas cloud ($m^3$) |
|---|---|---|
| 1 | 40 | 22 |
| | 2.5 | 0 |
| 10 | 40 | 95 |
| | 2.5 | 43 |

Through the analysis of hydrogen leakage processes under different leakage scenarios, it can be seen that the positions where combustible vapour can be detected in time after hydrogen leakage include potential leakage points (at the hydrogen cylinder valve and the pressure transmitter at the hydrogen cylinder filling inlet), directly above the leakage point, and at the ventilation outlet. Fixed combustible vapour detectors are

to be arranged at these positions. In addition, combustible vapour clouds may also accumulate at the top of other positions, and additional detectors may be considered.

### 3.2 Example of hydrogen leakage fire analysis

(1)Ventilation arrangement

The ventilation inlet, ventilation outlet, ventilation type and ventilation rate are determined according to the actual design.

(2)Accident consequence simulation and analysis

Under the scenario of leakage of high-pressure hydrogen (40 MPa) through a circular hole of 10 mm in diameter, the leakage point is located at the connection joint between the hydrogen cylinder and the hydrogen supply line. Immediate ignition after leakage leads to a fire. The thermal radiation cloud maps at different times after the occurrence of the hydrogen fire are shown in Figures 3.2-1 and 3.2-2 of this Appendix.

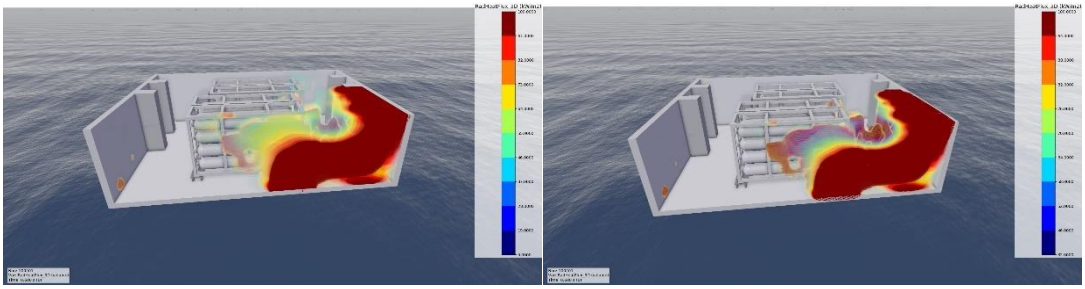

**Figure 3.2-1 Thermal Radiation Cloud Map at the Moment of Ignition (left: 5–100 kW/m², right: 32–100 kW/m²)**

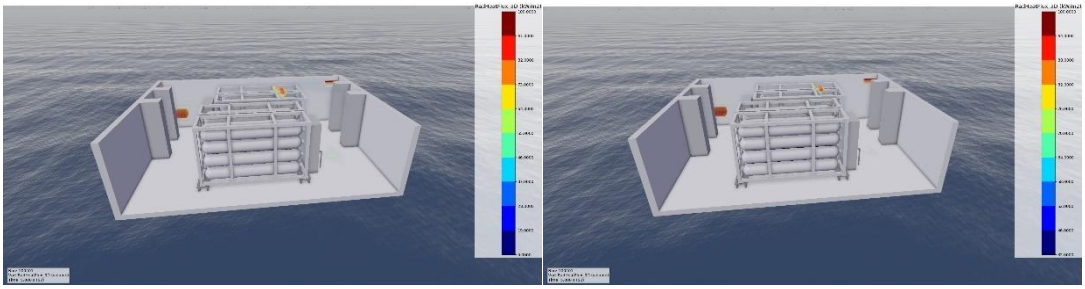

**Figure 3.2-2 Thermal Radiation Cloud Map at 5 s after Ignition (left: 5–100 kW/m², right: 32–100 kW/m²)**

The maximum thermal radiation during the entire fire process is approximately 498 kW/m². With 5 kW/m² as the boundary, the maximum thermal radiation range covers a volume of approximately 40 m³, affecting the bottom plate and side shell in the vicinity of the leakage point, as well as the top plate between the ventilation outlet and the ventilation inlet. With 32 kW/m² as the boundary, the maximum thermal radiation range covers a volume of approximately 30 m³, affecting the bottom plate and side shell in the vicinity of the leakage point, as well as the top plate between the ventilation outlet and the ventilation inlet.

(3)Fire consequence analysis

Based on the simulation of all identified hydrogen fire accident scenarios, the consequence analysis of different hydrogen fire events in the hydrogen storage space is shown in Table 3.2 of this Appendix.

**Table 3.2 Quantitative Data of Fire Accident Consequences in the Hydrogen Storage Space**

| Leakage aperture (mm) | Pressure (MPa) | Thermal radiation range at 5kW/m$^2$ | Thermal radiation range at 32kW/m$^2$ |
|---|---|---|---|
| 1 | 40 | Extremely small volume, affecting a small portion of the top plate | No effect. |

| | | | |
|---|---|---|---|
| | | between the ventilation inlet and the ventilation outlet. | |
| 10 | 40 | Affected volume of 40 m³, affecting the bottom plate and side shell in the vicinity of the leakage point, as well as the top plate between the ventilation outlet and the ventilation inlet. | Affected volume of 30 m³, affecting the bottom plate and side shell in the vicinity of the leakage point, as well as the top plate between the ventilation outlet and the ventilation inlet. |

The structures affected after the occurrence of fire mainly include the bottom plate and side shell in the vicinity of the hydrogen leakage point (at the hydrogen cylinder valve and the pressure transmitter at the hydrogen cylinder filling inlet), as well as the top plate between the ventilation outlet and the ventilation inlet. However, due to the reduction in the hydrogen leakage rate and the continuous consumption of oxygen in the space, the fire duration is maintained for only approximately 5 s, so the cumulative damage to the structures is limited. The personnel activity areas affected after the occurrence of the fire are mainly the vicinity of the leakage point and the areas near the ventilation outlet/inlet of the space. In combination with the structural characteristics of the ship's hydrogen storage space, the dispersion characteristics of hydrogen and the requirements for safe ship operations, it is recommended that gas/fire detection equipment be arranged in a targeted manner: gas detection equipment is to be arranged at key positions such as potential leakage points of hydrogen storage equipment, pipe joints and valves, while fire detection equipment is to be arranged in key air circulation areas such as the ventilation outlet and inlet of the hydrogen storage space, so as to achieve full coverage and blind-spot-free monitoring of hydrogen leakage and early fire conditions, provide early warning of leakage, fire and explosion risks, and ensure the operational safety of the ship's hydrogen storage space and surrounding areas.

### 3.3 Example of hydrogen leakage explosion analysis

(1)Ventilation arrangement

The ventilation inlet and ventilation outlet are arranged at the top of the space, and the ventilation inlet is arranged for natural air supply.

(2)Accident consequence simulation and analysis

Under the scenario of leakage of high-pressure hydrogen (40 MPa) through a circular hole of 10 mm in diameter, the leakage point is located at the connection joint between the hydrogen cylinder and the hydrogen supply line. Delayed ignition after leakage leads to an explosion. The maximum pressure distribution after the occurrence of the hydrogen explosion is shown in Figure 3.3 of this Appendix.

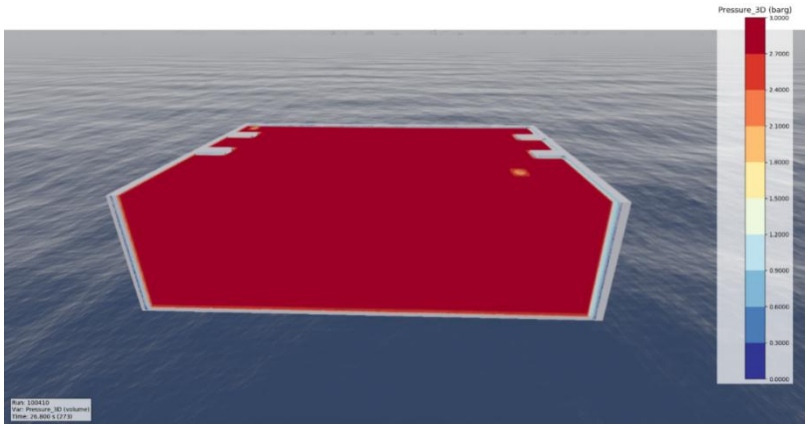


**Figure 3.3 Maximum Pressure Distribution in the Hydrogen Storage Space after Hydrogen Explosion (0.2–3 bar)**

After approximately 3 s of hydrogen leakage dispersion, the entire hydrogen storage space is completely covered by the combustible vapour cloud. At the moment of ignition, an explosion occurs. After the explosion, the maximum pressure in the space reaches approximately 2.8 bar.

(3)Fire consequence analysis

Based on the simulation of all identified hydrogen explosion accident scenarios, the consequence analysis of different hydrogen explosion events in the hydrogen storage space is shown in Table 3.3 of this Appendix.

**Table 3.3 Quantitative Data of Explosion Accident Consequences in the Hydrogen Storage Space**

| Leakage aperture (mm) | Pressure (MPa) | Maximum pressure (bar) |
|---|---|---|
| 10 | 40 | 2.8 |

Considering that the maximum overpressure value is relatively large (>0.5 bar), it is recommended that the space be designed to be explosion-proof, with explosion venting devices scientifically arranged, and that consideration be given to avoiding potential damage to the hull structure and personnel outside the space caused by venting fragments.

## 3.4 Example of individual risk value calculation

This case adopts the hydrogen accident database of Sandia National Laboratories referred to in 6.3.1.1, Chapter 6 of the Guidelines.

(1)Frequency analysis of leakage

Based on the equipment and fittings list, in combination with the hydrogen accident database, the leakage frequencies of different apertures for different equipment and fittings are calculated, as shown in Table 3.4-1 of this Appendix.

**Table 3.4-1 Leakage Frequencies of Equipment, Piping and Fittings in the Hydrogen Storage Space**

| Leakage object | Cumulative leakage frequency (per year) | | |
|---|---|---|---|
| | 1% aperture | 10% aperture | 100% aperture |
| Hydrogen cylinder outlet valve | $1.7\times10^{-3}$ | $8.0\times10^{-4}$ | $1.5\times10^{-4}$ |
| Hydrogen cylinder tail valve | $1.7\times10^{-3}$ | $8.0\times10^{-4}$ | $1.5\times10^{-4}$ |

(2)Accident frequency analysis

In combination with the hydrogen accident database, the event tree analysis method is used to carry out the frequency analysis of disaster accidents after leakage, as shown in Figure 3.4-1 of this Appendix. The results of accident frequency analysis are shown in Table 3.4-2 of this Appendix.

**Table 3.4-2 Results of Hydrogen Leakage Accident Frequency (per year) Analysis in the Hydrogen Storage Space**

| | Description | Ignition time | Output | Leakage frequency (per year) | Ignition probability | Cumulative frequency (per year) |
|---|---|---|---|---|---|---|
| Explosion | Delayed ignition after leakage of high-pressure hydrogen through a 10 mm aperture | Delayed | Pressure | $3.00\times10^{-4}$ | 0.027 | $8.1\times10^{-6}$ |
| Fire | Immediate ignition after leakage of high-pressure hydrogen through a 10 mm aperture | Immediate | Thermal radiation | $3.00\times10^{-4}$ | 0.053 | $1.6\times10^{-5}$ |
| | Immediate ignition after leakage of high-pressure hydrogen through a 1 mm aperture | Immediate | Thermal radiation | $1.60\times10^{-3}$ | 0.008 | $1.3\times10^{-5}$ |
| Dispersion | Dispersion after leakage of high-pressure hydrogen through a 10 mm aperture | — | Concentration | $3.00\times10^{-4}$ | — | — |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Dispersion after leakage of high-pressure hydrogen through a 1 mm aperture | — | Concentration | $1.60\times10^{-3}$ | — | — |

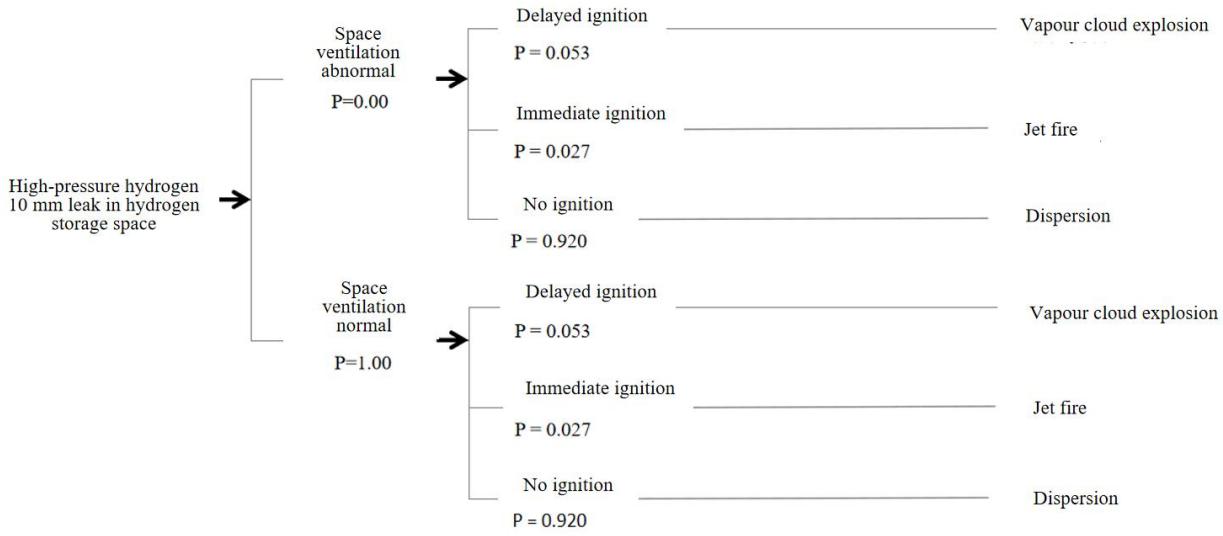


**Figure 3.4-1 Event Tree for Leakage of High-Pressure Hydrogen through a Circular Hole of 10 mm in Diameter in the Hydrogen Storage Space**

(3)Individual risk value calculation

In this case, Table 6.5.4.2(3), Chapter 6 of the Guidelines is adopted as the individual risk acceptability criteria. According to the maximum tolerable death risk for new ships, the allowable frequency of individual risk is set at $10^{-4}$/year.

① Analysis of the accident impact area of the hydrogen storage space under typical event tree scenarios

Taking the accident derived from hydrogen leakage through a circular hole of 10 mm in diameter in the high-pressure pipeline inside the hydrogen storage space as a typical event tree scenario, based on the frequency of occurrence of each disaster consequence in the event tree, the accident impact consequences are calculated by simulation. The impact areas of each disaster after considering the frequency are obtained by simulation, and converted to obtain the probability that the space is completely within the lethality threshold for personnel.

For asphyxiation, at a reference probability of $10^{-4}$ per year, the impact area of asphyxiation is shown in Figure 3.4-2 of this Appendix. The entire hydrogen storage space is substantially above the concentration threshold for personnel death by asphyxiation, with only a very small area below the threshold.

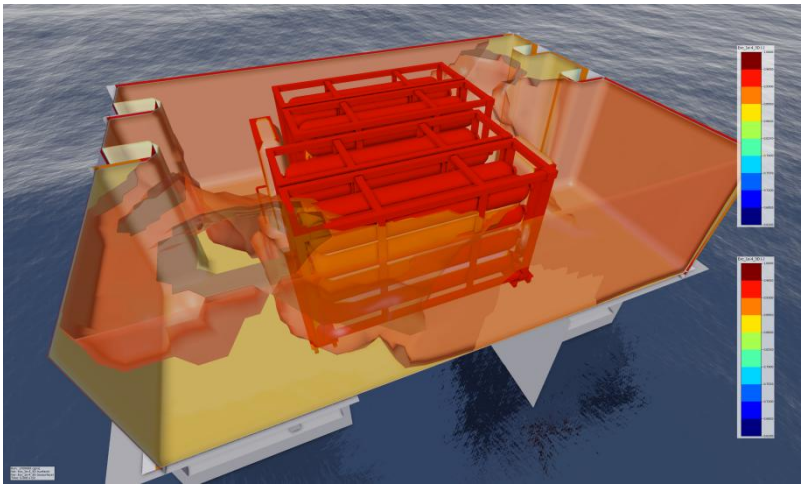

**Figure 3.4-2 Impact Area of Asphyxiation Consequence (>62%)**

For fire thermal radiation, at a reference probability of $10^{-4}$ per year, no thermal radiation exceeding 12.5 kW/m² (1% death probability) appears in the entire space. At a reference probability of $10^{-5}$ per year, the impact area of thermal radiation of 12.5 kW/m² is shown in Figure 3.4-3 of this Appendix.

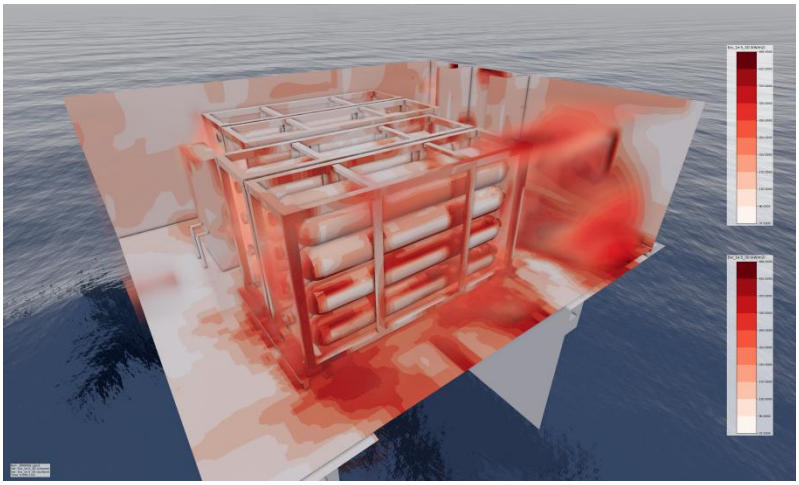

**Figure 3.4-3 Impact Area of Fire Consequence (12.5–37.5 kW/m²)**

Taking the thermal radiation of 25 kW/m² (100% lethality) as the criterion, the probability of occurrence that the entire space is covered by thermal radiation is $7.4\times10^{-5}$ times/year, as shown in Figure 3.4-4 of this Appendix.

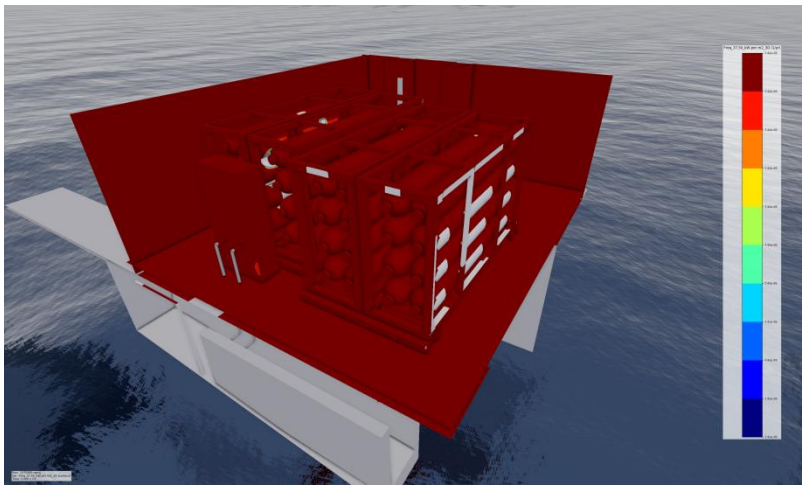

**Figure 3.4-4 Full Coverage of the Fire Consequence Lethality threshold (>25 kW/m²)**

For explosion overpressure, at a reference probability of $10^{-4}$ per year, no explosion overpressure of 0.3 bar (100% lethality) appears in the space. At a reference probability of $10^{-5}$ per year, the impact area of explosion overpressure exceeding 0.3 bar in the space is shown in Figure 3.4-5 of this Appendix.

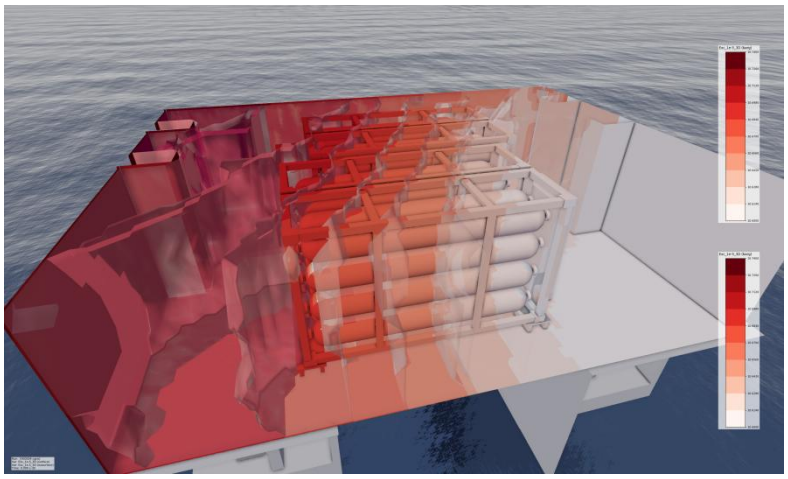

**Figure 3.4-5 Impact Area of Explosion Consequence (0.3–10.73 bar)**

Taking the explosion overpressure of 0.3 bar as the criterion, the probability of occurrence that the entire space is covered by overpressure is $3.78\times10^{-5}$ times/year, as shown in Figure 3.4-6 of this Appendix.

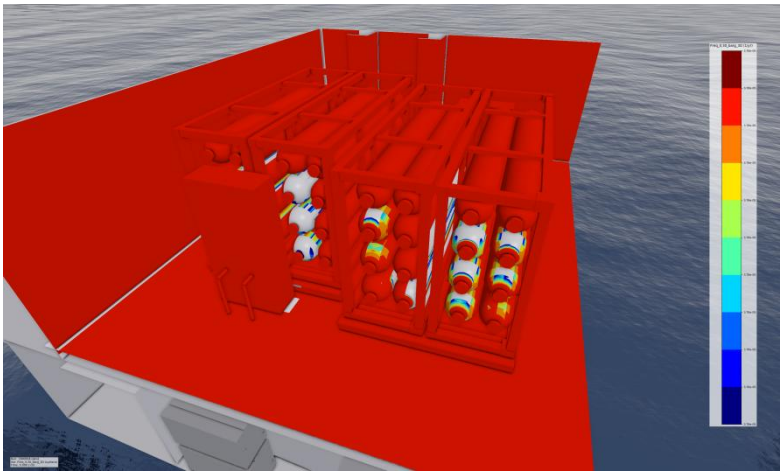

**Figure 3.4-6 Full Coverage of the Explosion Consequence Lethality Threshold (>0.3 bar)**

② Calculation of the probability of

The frequency of personnel entering the hydrogen storage space for operation, inspection and repair, bunkering, etc. is analyzed. In combination with the duration required for each operation or repair, the total time personnel are present in the hydrogen storage space each year is determined and converted into the probability of personnel presence. In this case, it is assumed that there are 12 inspections, 2 repairs and 50 bunkering operations per year, each lasting 30 minutes. The calculated probability of personnel presence is 6.84%.

③ Calculation of death probability for personnel in the hydrogen storage space under typical event tree scenarios

The probabilities of death of personnel caused by thermal radiation and explosion overpressure in each area are determined in accordance with 6.4.3, Chapter 6 of the Guidelines. In areas with overpressure exceeding 0.03 MPa, the probability of death is 1. In areas with thermal radiation in the range of 12.5–25 kW/m², the probability of death of personnel is 1%; in areas with thermal radiation exceeding 25 kW/m², the probability of death of personnel is 100%. In high-concentration asphyxiation areas (hydrogen

concentration > 62%), the probability of death of personnel is 1.

④ Calculation of individual risk value under typical event tree scenarios

Based on the impact areas, the probability of personnel located in each area and the probability of death of personnel located in each area, the calculated individual risk values are shown in Table 3.4-3 of this Appendix.

**Individual Risk Values of Different Hydrogen Accidents in the Hydrogen Storage Space**

**Table 3.4-3**

| | Criterion | Occurrence frequency (per year) | Probability of death of personnel | Probability of personnel presence | Individual risk value (per year) |
|---|---|---|---|---|---|
| Asphyxiation | 62% | $1\times10^{-4}$ | 100% | 6.84% | $6.84\times10^{-6}$ |
| Thermal radiation | 25kW/$m^2$ | $7.42\times10^{-5}$ | 100% | 6.84% | $5.07\times10^{-6}$ |
| Explosion overpressure | 0.3bar | $3.78\times10^{-5}$ | 100% | 6.84% | $2.54\times10^{-6}$ |

⑤ Calculation of the cumulative risk value of all accidents

By superimposing the individual risk values under all event tree scenarios, the total individual risk value of each area within the hydrogen storage space is calculated to be $1.45\times10^{-5}$ per year, which is lower than $10^{-4}$ per year. The individual risk therefore meets the safety requirements.