Research on the Safety Goal Framework of Nuclear-Powered Icebreaker

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Abstract: Nuclear-powered icebreakers are responsible for tasks such as breaking ice, opening shipping lanes, and piloting in polar and icy regions. Unlike fixed nuclear reactor on land, the assessment of their safety requires not only reactor safety but also a further consideration of the correlation between reactor safety and ship hull safety from the perspective of operational feasibility. Based on the analysis of requirements related to reactor and ship safety, this paper attempts to establish a safety goal framework for nuclear-powered icebreakers including three levels, and the assessment methods for specific goal have been proposed. The result of this research can provide technical support for the safety assessment of nuclear-powered icebreakers.

Keywords: Safety goal, Nuclear-Powered Icebreaker, Comprehensive safety.

1. INTRODUCTION

Nuclear-powered icebreakers are responsible for tasks such as breaking ice, opening navigation channels, piloting, and scientific research in polar and ice-covered regions. They also have certain capabilities for maritime support and ocean mapping. They are typically equipped with two independent nuclear reactor units as the power source which provide continuous and stable power output for the ship's navigation and icebreaking operations, and ensure the safety of the ship and its crew.

The nuclear-powered icebreaker is a combination of "reactor" and "ship." It must not only consider the safety of the reactor but also consider the safety of the ship and the operation of icebreaking. Because in the situations where propulsion is lost, not only will the icebreaking operation fail, but the ship may also capsize, further threatening the safety of the reactor and the lives of the crew and environmental safety. Therefore, as the power source for the ship, the reactor and the ship which carries the reactor are interdependent. This determines that the safety analysis of the nuclear-powered icebreaker necessarily focuses on the "overall safety" of the "ship safety" and "reactor safety" being coordinated.

Safety Goal are the top-level requirements for the design and operation of nuclear facilities. Given the comprehensive safety evaluation requirements for nuclear-powered icebreakers, the top-level safety goal framework should cover safety requirements related to reactor safety and ship safety. Currently, there are relatively mature safety analysis systems established in the fields of reactors and ships, but there is a lack of integration on nuclear-powered ships, which combine the two aspects. The comprehensive safety goal framework for nuclear-powered icebreakers has not proposed yet. For example, the safety requirements of reactor originates from land-based nuclear facilities represented by nuclear power plants, with an emphasis on "radioactive release and the resulting radioactive consequences" as the evaluation target. This cannot adequately reflect the complementary relationship between reactor safety and ship safety in nuclear-powered icebreakers.

In summary, for nuclear-powered icebreakers which are a combination of a reactor and a ship, establishing a comprehensive safety goal framework and clarifying the scope of safety evaluation is of great significance. This paper will based on the existing research achievements in the fields of reactors and ships to study the comprehensive safety goal framework for nuclear-powered icebreakers.

2. RESEARCH OF REACTOR AND SHIP SAFETY GOALS

2.1 Safety goals of a nuclear power plant

The safety requirements of a nuclear power plant include aspects such as design basis, radiation protection, and defense in depth. Among these, the probability safety objectives are an important quantitative indicator for measuring the safety level of reactors. The risk assessment method and probability safety objectives in the nuclear industry are based on the development of water-cooled reactors, therefore, the specific indicators used in their probability safety objectives are Core Damage Frequency (CDF) and Large Early Release Frequency (LERF).

The United States is the most extensive and developed country in the use of nuclear energy, with a deeper and more comprehensive understanding of nuclear safety and regulatory framework. It was the first to quantify nuclear safety objectives and to combine deterministic and probabilistic approaches in technical safety goal research. Therefore, the nuclear safety goal framework of nuclear power plants in various countries have drawn on the existing research and practice of the U.S. Nuclear Regulatory Commission (NRC) to some extent. The NRC’s Policy Statement on Safety goal sets two qualitative safety objectives and two quantitative safety objectives. The principle underlying these safety objectives is that the risk of threat from nuclear reactors should not be significantly higher than other societal risks. The two quantitative safety objectives are known as Quantitative Health Objectives (QHOs)[1-3]:

(1) The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1%) of the sum of prompt fatality risks resulting from other accident to which members of the U.S. population are generally exposed.

(2) The risk to the population in the area of nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1%) of the sum of cancer fatality risks resulting from all other causes.

To enable the evaluation of safety objectives in actual analyses, the NRC has proposed two subsidiary objectives (CDF and LERF) as criteria for safety assessment, and has provided a rationale for the relationship between the QHO and CDF and LERF.

The CDF and LERF, which are the probabilistic safety objectives for the development of water-cooled reactors, are also referenced by other countries and institutions, including the International Atomic Energy Agency (IAEA)[4]. It can be seen that the probabilistic safety objective for land-based reactors are linked to the social risk for the public, which can more reasonably reflect the potential risk impact of reactors on the general public.

2.2 Safety analysis methods and safety objectives of ship

The field of shipping industry has also established safety analysis methods, with the most representative being the Formal Safety Assessment (FSA). The International Maritime Organization (IMO) is the specialized agency of the United Nations responsible for maritime navigation safety and the prevention of marine pollution by ships. It has revised the “Revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process, MSC-MEPC.2/Circ.12, Rev.2”[5] in 2018. This document provides a detailed description of the FSA process and risk assessment methods for ships. The methodological approach is similar to Probabilistic Safety Analysis (PSA), both in terms of evaluating risks based on frequency and consequences of events. However, the FSA mainly employs qualitative and semi-quantitative methods in practice.

According to the survey, the shipping industry has not yet established quantitative safety goals or a safety indicator system. Instead, it mainly provides qualitative requirements from perspectives such as reliability, availability, and economy. For nuclear-powered merchant ships, the safety goals primarily focus on the limitation of radioactive release and its consequences. In 1981, IMO issued the “Nuclear Ship Code, Code of Safety for Nuclear Merchant Ships,”[6] and revised the code for new vessels in 2016. This document sets requirements for dose limits in various conditions for the bridge, living quarters, deck and cargo hold, ship’s side, and bottom areas. Regulatory requirements in the UK[7], Russia[8,9], the United States[10-14], and other countries[15] mainly provide qualitative requirements or quantitative dose limits for crew members, relevant operational personnel.

3. ANALYSIS OF NUCLEAR-POWERED ICEBREAKER MISSION PROFILES AND SAFETY ELEMENTS

3.1 Nuclear-Powered Icebreaker Mission Profiles

Nuclear-powered icebreakers, as mobile nuclear facilities at sea, can generally divide their mission profiles and corresponding operational environments into two categories: operational voyaging and coastal or harbor operations. Under these two mission profiles, the task requirements and safety requirements for nuclear-powered icebreakers are significant differences.

(1) For operational voyaging conditions, the primary task of the nuclear-powered icebreaker is to ensure the feasibility of ice-breaking operations, with the reactor serving as the fundamental guarantee for mission execution. On the other hand, the reactor is relatively distant from the general public, which means that in the event of an accident, the impact on the public and the environment would be relatively small. Therefore, it is crucial to focus on the radiological impact of the reactor on the crew and passengers in abnormal conditions, as well as the impact of loss of propulsion on the safety of the vessel and the success of the ice-breaking mission. Moreover, in this scenario, since the vessel is far from land, it would be difficult to receive external assistance in the event of an accident. Therefore, under conditions where the feasibility of ice-breaking operations cannot be guaranteed, the safety of the vessel itself becomes the bottom line for safety.

(2) In coastal or harbor operations, the vessel often remains at anchor, in a state of shutdown, or undergoing maintenance. Under these conditions, the reactor operates at low power or shut down, and its location is closer to the general public. Therefore, it is crucial to focus on the radiological impact of the reactor on the crew, passengers, and the surrounding public and environment in the abnormal events.

Nuclear-powered icebreakers operate under a more diverse range of conditions and in a more complex environment, compared to land-based reactors. The vessel, crew, passengers, the public and environment are dynamically interconnected in terms of safety. This safety consideration not only involves the reactor's safety but also the safety of the vessel, which relies on the reactor as a power source. The safety objectives for nuclear-powered icebreakers should be able to reasonably reflect the interrelation between these elements.

3.2 Safety elements for nuclear-powered icebreakers

As a maritime vessel with specific task attributes, the safety goal framework for nuclear-powered icebreakers should be led by the executability of ice-breaking operations, and it should comprehensively consider the coupling relationship between ship hull safety and reactor safety from the perspectives of personnel and environmental safety. The correlation between various safety elements in the framework across different mission profiles is illustrated in Figure 1.

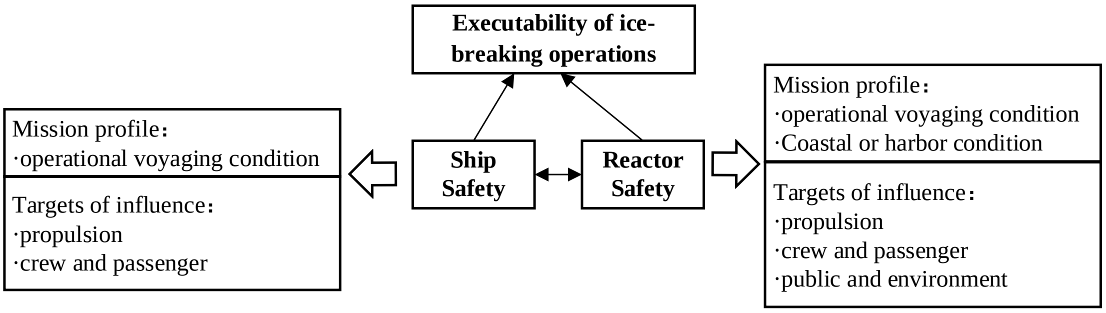

Figure 1. Comprehensive safety goal framework relationship of a nuclear-powered icebreaker

3.2.1 Operational voyaging conditions

In this condition, the safety and risk concerns should focus on the “executability of operations” as the analysis goal. If the executability of icebreaking operations cannot be guaranteed (i.e., the power cannot support the icebreaking), the focus will shift to “ship hull safety” to ensure the safety of the crew and passengers. In this stage, the loss of the reactor and power propulsion system may directly lead to the failure of operational executability and the loss of ship hull safety. The safety requirements for this condition include the following main factors:

(1) Unplanned total loss of propulsion

If the power system failure or common cause leads to an unplanned emergency shutdown of both reactors during icebreaking operations, it will result in the loss of propulsion for the ship. If power cannot be restored for an extended period, not only will the operation fail, but the ship may also capsize due to the loss of propulsion, which directly threatening the safety of the crew and passengers.

(2) Unplanned partial loss of propulsion

This event refers to a situation where the reactor of a nuclear-powered icebreaker experiences a reduction in power due to unplanned reasons which prevent the completion of icebreaking operations. Nuclear-powered icebreakers typically have a dual-reactor and dual-turbine configuration. In certain failure states, it may lead to the failure of a single reactor and turbine, resulting in insufficient power to support the execution of icebreaking operations. However, it still maintains enough power to ensure the navigation of the ship, thereby ensuring the safety of the vessel.

(3) Core damage (CD) and radioactive large release (LR)

From the perspectives of crew and passenger safety and the safety of the vessel, the primary concerns of Core Damage (CD) and Large Radioactive Release (LR) which would be the complete or partial loss of propulsion for the ship, along with the exposure of the crew/passengers to excessive radiation. Furthermore, if a CD or LR were to occur during icebreaking operations, it could also draw the attention of the international community, potentially leading to unnecessary international incidents.

(4) Exceedance of crew/passenger dose limit radioactive release

Even in the event of a reactor accident where core damage and large radioactive release may not occur, there is still a possibility of abnormal radioactive emissions during the accident mitigation process. It is essential in the design of nuclear-powered vessels to establish clear acceptable radiation limits for crew and passengers.

(5) Habitability of the living spaces

In the event of a reactor accident or abnormal condition, it may also result in the emission of high-temperature, high-pressure water or steam except the potential for radioactive release, which would affect the habitability of the living spaces. These events may lead to the failure of icebreaking operations, and even impact the safety of the vessel.

3.2.2 Coastal or harbor condition

The “reactor safety” will be focused on in this scenario, with a particular emphasis on the radioactive hazards that could be posed to dock personnel, the surrounding public, and the environment in the event of a reactor accident. In this scenario, the nuclear-powered icebreaker is either at sea or moored in a port, hence the primary concern is to prevent any abnormal conditions that could arise in the reactor, which could lead to unacceptable radioactive hazards for the surrounding public and environment. Therefore, it is feasible to refer to the probabilistic safety objectives used for land-based reactors in this scenario, specifically including the risks of core damage and large radioactive release.

At this stage, the reactor is operating at low power or in a shutdown state. Furthermore, due to the smaller power output of marine reactors, the overall risk of accidents to the public is expected to be much smaller during this phase.

4. SAFETY GOAL FRAMEWORK OF NUCLEAR-POWERED ICEBREAKER

Based on the analysis in Chapter 3, this section attempts to establish a nuclear safety goal framework for nuclear-powered icebreakers consisting of three levels, as shown in Figure 2.

4.1 Top-level safety goal

Nuclear-powered icebreakers not only need to consider the safety of the reactor but also the operational feasibility based on the safety of the ship. Therefore, the top-level safety goal for nuclear-powered icebreakers should ensure the completion of ice-breaking operations while simultaneously guaranteeing the safety of the crew, the public, and the environment. The top-level safety goal for nuclear-powered icebreakers can be defined as follows:

“In the various operational stages of a nuclear-powered icebreaker, it is essential to establish and maintain effective safety measures to ensure the feasibility of operations and to protect the crew, passengers, public, and environment from radiological threat.”

4.2 Secondary safety goals and subsidiary objectives

For a nuclear-powered icebreaker, the safety factors and characteristics differ between the operational voyaging condition and the coastal or harbor condition. Therefore, the top-level safety goal should be divided into two secondary goals to address these distinct conditions separately. To facilitate the application of these safety goals, the secondary objectives for each stage should be further translated into specific subsidiary objectives.

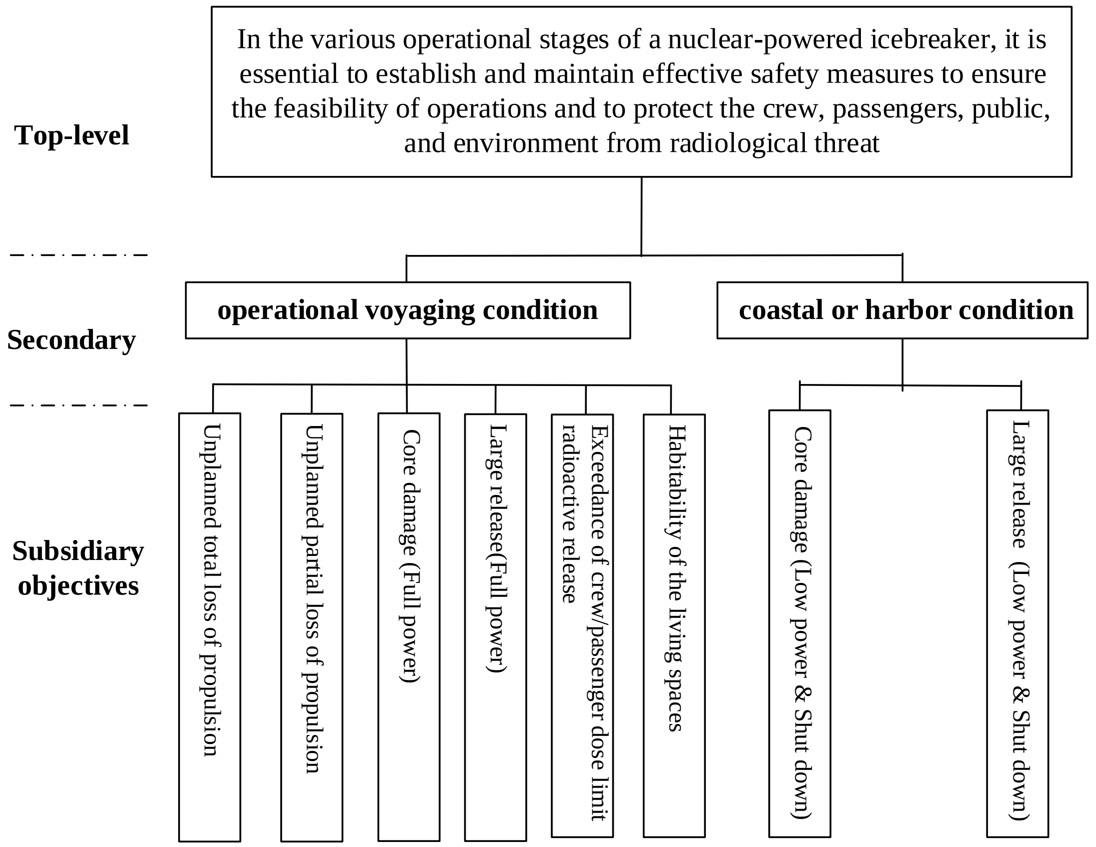

Figure 2. Safety goal framework of nuclear-powered icebreaker

<u>4.2.1 Secondary safety: operational voyaging condition</u>

“Nuclear-powered icebreaker should establish and maintain a set of effective safety measures during operational voyaging condition to ensure the safety of the vessel and its crew/passengers.”

Six subsidiary objectives are proposed, with all expressions in terms of likelihood of occurrence.

(1) Unplanned total loss of propulsion. The indicator measures the likelihood of unplanned dual reactor shutdowns or power system failures during the execution of ice-breaking operations. Such failures can result in the complete loss of power to the vessel, leading to mission failure and posing a threat to the safety of the vessel and its crew.

(2) Unplanned partial loss of propulsion. The indicator measures the likelihood of a nuclear-powered icebreaker experiencing an unplanned reduction in power which prevents the completion of ice-breaking operations. Under such a failure, the remaining power is insufficient to support the execution of the ice-breaking task, but is still sufficient to ensure the safety of the vessel.

(3) Core damage (CD). The indicator measures the likelihood of core damage to the reactor during the execution of ice-breaking operations due to an accident.

(4) Radioactive large release (LR). The indicator measures the likelihood of radioactive large release to the reactor during the execution of ice-breaking operations due to an accident.

(5) Exceedance of crew/passenger dose limit radioactive release. The indicator measures the likelihood of crew/passengers on a nuclear-powered icebreaker receiving doses of radiation that exceed allowable limits in different accident scenarios.

(6) Habitability of the living spaces. The indicator measures the likelihood of reactor accidents leading to environmental impacts such as high temperature and humidity, which affect the habitability of the ship's living spaces.

4.2.2 Secondary safety: coastal or harbor condition

"Nuclear-powered icebreakers should establish and maintain a set of effective safety measures during the coastal or harbor condition to protect workers, the public, and the environment from radioactive threat".

In this condition, there is no essential difference between the shipboard reactor and the land-based reactor, therefore, the subsidiary objectives can be similar to those for land-based fixed reactors, considering both core damage and Large radioactive release.

5. PRELIMINARY EVALUATION METHODS OF SUBSIDIARY OBJECTIVES

According to the analysis in Chapter 4, the safety target system of nuclear-powered icebreakers includes a total of six secondary indicators, which can be divided into three categories:

(1) Category I: Unplanned total loss of propulsion, Unplanned partial loss of propulsion.

(2) Category II: Core damage Frequency (CDF), Large release frequency (LRF).

(3) Category III: Exceedance of crew/passenger dose limit radioactive release, Habitability of the living spaces.

5.1 Category I subsidiary objectives

The evaluation of these objectives focuses on the reliability of the power system, primarily involving unplanned emergency shutdowns of the reactors and failures in the power transmission system. The specific content and evaluation methods are as follows:

(1) Unplanned emergency trip

a) Unplanned emergency Trip caused by control system failures. For various control signals that may lead to false trips, a combination of Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) is used to identify equipment failures and their combinations that could lead to unplanned emergency trip of single reactor or both reactors. Based on the reliability parameters of the equipment, the likelihood of these occurrences is quantified.

b) The probability of initiating events that would trigger an emergency trip. The evaluation of this indicator can be based on the frequency of initiating events identified in reactor PSA, particularly the frequency of transient events that contribute the most.

(2) Failure of Power transmission system

The evaluation is conducted using traditional reliability analysis methods, such as Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), etc. The evaluation scope includes relevant critical systems in the power transmission system other than the reactor.

5.2 Category II subsidiary objectives

Core Damage Frequency (CDF) and Large Release Frequency (LRF) are the two most important indicators for characterizing reactor safety. The evaluation methods for these two objectives still adopt the PSA approach. However, due to the operational dependency of the nuclear-powered icebreaker on the scheduling of scientific research tasks, there can be significant variations in the number of operations executed and the duration of each operation from year to year. Therefore, it is recommended to use “1/reactor·voyage” instead of “1/reactor·year” for the evaluation of these objectives.

5.3 Category III subsidiary objectives

These objectives focus on the potential loss of habitability in the cabin of a nuclear-powered icebreaker due to radioactive releases exceeding limits, high temperatures, and high humidity under accident or abnormal operating conditions. The evaluation of such indicators can be conducted using the PSA method, but it requires further refinement in the PSA accident scenario modeling, considering the impact of radioactive releases exceeding limits, high temperatures, and high humidity in the analysis of the consequences of accident scenarios.

6. CONCLUSION

This paper attempts to establish a safety goal framework of nuclear-powered icebreakers. The nuclear safety goal framework of nuclear-powered icebreakers should be centered around the executability of ice-breaking operations, considering requirements for both the inherent safety of the reactor and the operational safety of ship. There are distinct differences in the consequences of accidents during different operational conditions of a nuclear-powered icebreaker. Therefore, the safety goal framework should necessarily differentiate between different operational conditions to establish applicable specific objectives. Furthermore, nuclear safety on nuclear-powered icebreakers requires an integrated consideration of the interrelation and combination of the safety of the vessel, the crew/passengers, and the public.

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