Study on Rating Method of Nuclear Events in Marine Nuclear Power Plant

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Abstract. According to the operational safety characteristics of marine nuclear power plant and the nuclear safety rating needs of nuclear ships in case of abnormal events during sea navigation, the rating evaluation standards are established referring to the international nuclear event rating table, which consider three aspects of "radioactive safety impact", "defense in depth capability impact" and "power output impact" in abnormal events. The potential common cause characteristics of the event are additionally considered. Then the rating procedure for nuclear safety events of marine nuclear power plant is proposed. The study is of great significance for accurately evaluating the severity of abnormal events and effectively guaranteeing nuclear safety of marine nuclear power plant.

1. Introduction

Accurate and fast reporting of nuclear incidents is the basis for correct response and mitigation of nuclear accidents. The civilian nuclear power sector established a nuclear safety accident (event) rating standard for nuclear power plants [1], which is based on the international nuclear and radiological event scale (INES), and the radiological consequences of nuclear events and the degradation of defense-in-depth capabilities. This method in rating has been widely used at home and abroad. When an anomalous event occurs during the maritime navigation of a nuclear-powered ship, due to limited communication capabilities and tight requirements for support time, a marine nuclear power plant requires a more simple and accurate reporting capability for nuclear safety events than a nuclear power plant. However, due to the special application environment and mission of marine nuclear power plants, it is not sufficient to directly draw on the above rating standards when conducting nuclear event rating. Therefore, in this paper, we study the nuclear safety features of marine nuclear power plants, and establish a classification method and standard system for nuclear safety events, which provides a reference for the nuclear safety event classification of nuclear power plants.

2. Nuclear power plant’s classification and rating method

In the process of nuclear energy development, a variety of nuclear accident classification and rating methods have been developed as needed. In view of the safety evaluation of the nuclear power plant design process, the American Standards Institute classifies the operating conditions of nuclear power plants into four categories according to the radiological consequences of nuclear accidents and the expected probability of occurrence: normal operation and transients, expected operational events, rare
accidents, and extreme accidents. Different acceptance criteria are applied to different working
conditions, and accidents with serious consequences must be taken to ensure that the probability of
occurrence is extremely low. In addition, from the perspective of safety review, the US nuclear
regulatory commission (NRC) classifies typical accidents of nuclear power plants according to the
response characteristics of accidents. These accidents are also the main contents of accident safety
analysis in the safety analysis report.

Lessons from the Chernobyl and Three Mile Island nuclear accidents show that without a uniform
nuclear accident (event) rating standard, it often leads to a nuclear accident that is either misinterpreted
or misunderstood, or concealed by malicious people. To this end, the public has responded strongly
and requested that nuclear accidents in nuclear power plants be notified in time. In order to facilitate
public understanding, some countries have successively established a simplified indicator of the
severity of nuclear incidents that is easy to understand. In early 1990, the international atomic energy
agency (IAEA) and the nuclear energy agency (NEA) of the organization for economic co-operation
and development (OECD) jointly developed the international nuclear event scale INES, which was
revised in 2008. The table divides nuclear events occurring at nuclear power plants into seven levels
based on three criteria: criterion 1 is “potential impacts of people and the environment” and is assessed
as grades 2 to 7; the criterion 2 is “barriers and control effects of radioactive materials”. , rated as 2 to
5; criterion 3 is "potential impact of defense in depth", rated as 1 to 3. Then the three criteria are listed
in a table. The “human and environmental” impact criteria and the “radioactive substance barrier and
control” impact criteria are the impact of nuclear events from the perspective of radiological safety.
The “deep defense capability” impact criterion is the device. From the perspective of the ability to
withstand nuclear accidents, the impact of nuclear events is assessed, the assessment level is
standardized, accurate, mature, concise, and the level correspondence is good.

For thermal-hydraulic models, the primary coolant system and middle loop system are simulated in
detail. Coolant channels of the core consist of average channel, hot channel and bypass channel. Core
power is calculated by point kinetic model with feedback input. Self-pressurized spaces of the RPV
are divide into independent gas space, mixture space and independent water space. Top volumes of the
self-pressurized space are connected with valve components to simulate the pressure protection system.
Coolant channels of the main heat exchanger are modeled as two parts to simulate the double-tube
bundle structure. Main components of the middle loop system are also considered, including
secondary side of the main heat exchanger, pressurizer, inlet plenum, U-tubes, out plenum, and
circulating pump. As for secondary loop system, the feedwater supply and steam outlet are simplified
as boundary conditions.

3. Nuclear safety features of marine nuclear power plants

Compared with nuclear power plants, marine nuclear power plants have their own unique
characteristics. These characteristics have a significant impact on the accident response process and
potential consequences, and they are also important factors that must be considered when conducting
nuclear safety event classification methods.

3.1. Coupled nuclear safety and hull safety

For nuclear power plants, nuclear safety is the paramount priority at all times. The fundamental goal is
to control the release of radioactive materials, in other words, shutting down the reactor quickly when
an event that may lead to an increased risk of uncontrolled release of radioactive material occurs.
However, for nuclear-powered ships, the hull is the carrier for the safe operation of nuclear power
plants and the survival of ship personnel. The hull safety is the premise to ensure the safety of nuclear
power plants. The nuclear power plant is the main power source of the ship, and the important basis
for the hull safety. The reactor cannot be easily shut down during maritime navigation, and the nuclear
power plant is allowed to operate in super-technical specifications in an emergency to maintain the
power output capability. In particular, nuclear-powered ships often require the achievement of flexible
missions as the first goal of the entire ship during operation, and nuclear reactors may face more
severe nuclear safety risks in emergencies. Therefore, the hull safety and reactor safety are mutually
dependent and mutually influential. Under some accident conditions, there is also a resource
competition relationship, which leads to a requirement for comprehensive consideration of nuclear
safety targets for marine nuclear power plants.

3.2. Highlights of common cause events
Due to the small space and dense equipment of the ship cabin, it is difficult to set up safety facilities in
accordance with the single failure criterion and independence principle, resulting in prominent
common cause events and strong coupling effects between systems. For example, once a high
temperature and high pressure coolant leaks in the tank, it may cause a cascading failure of the
electrical equipment in the cabin, which will increase the scope of the event. This characteristic makes
it strongly uncertain when assessing the impact of nuclear safety defense capabilities.

3.3. Frequent changes in working conditions
For marine nuclear power plants, the reactor output power must meet the requirements of a large and
frequent change in ship load. The reactor may operate at a lower rated power state for a long period of
time. The conversion of ship mooring and navigation causes the reactor to frequently start and stop.
The change of operating conditions of nuclear power plants will cause the thermodynamic
characteristics of internal working fluids to change constantly. From the perspective of mechanics,
frequent changes in operating conditions will have a negative impact on the safety of nuclear power
plant equipment and pipelines. However, sometimes the operating requirements of low working
conditions are beneficial to safety. This characteristic leads to the full consideration of the mission
profile of the device when assessing the potential nuclear safety consequences of an event.

4. Method for nuclear event rating of marine nuclear power plant
According to the above-mentioned nuclear safety characteristics of marine nuclear power plants, for
the nuclear safety event classification we can not only consider the release of radioactive materials, but
also the impact on the hull safety, mission, and possible common cause effects. Therefore, referring to
the classification method of INES, based on the establishment of the classification criteria for nuclear
events of marine nuclear power plants, the effects of the events on “radioactive safety”, “deep
defense” and “power output” are considered with additional consideration for the potential common
cause of the event.

4.1. Radioactive safety impact assessment criteria
According to the radioactive release characteristics and possible safety effects of marine reactor
accidents, referring to the evaluation criteria for radiological consequences in INES [2], we determines
the severity of the radiological consequences and the level of the accident mainly from the radioactive
release to the environment after the accident, the radiation dose of the individual, the degree of core
damage, and the radiation dose rate in the work area.

4.1.1. Radioactive environmental release. According to the INES standard, if the environmental
release caused by the accident exceeds the equivalent of $10^{16}$Bq$^{131}$I, it should be set to level 7; if the
environmental release exceeds the equivalent of $10^{15}$Bq$^{131}$I, the accident should be set to level 6; if the
environmental release exceeds the equivalent of $10^{14}$Bq$^{131}$I, the lowest rating of the accident is level 5;
if the environmental release exceeds the equivalent of $10^{13}$Bq$^{131}$I, the lowest rating of the accident is
level 4. For the consequences of environmental radioactive release, the marine reactor rating standards
will directly draw on the INES standard, assuming that the environmental release is given $Q_{en}$
considering the environmental release given the rating $S_{en}$. The classification criteria for the release of
the radioactive environment under marine reactor accidents can be obtained, as shown in Equation 1.
4.1.2. Individual exposure dose. According to INES standards, if a person is applied a fatal deterministic effect, the minimum should be level 4; if the individual has a non-fatal deterministic effect or a worker's effective dose exceeds 10 times the statutory annual systemic dose limit, the minimum should be set to level 3; if a public member is exposed to an effective dose of more than 10 mSv or a staff member is exposed to a statutory annual dose limit, the minimum should be level 2; if a member of the public receives more than The statutory annual dose limit or the exposure of a staff member exceeds the dose constraint value, and the minimum should be level 1. For the evaluation model and dose limits of individual exposure doses, referring to the relevant provisions in GJB1067.1-91 and GJB1067.4-91 [3, 4], assuming that the personal effective dose received by the staff is \( H_w \), the individual effective dose is \( H_p \), given the individual dose given the rating of \( S_{person} \). The rating standard for individual exposure doses under marine reactor accidents can be obtained, as shown in Equation 2.

\[
S_{person} = \begin{cases} 
4 & \text{(One person died from radiation)} \\
3d(H_w > 500\text{mSv}) \\
2d(H_w > 50\text{mSv}, H_p > 10\text{mSv}) \\
1d(H_p > 5\text{mSv}) 
\end{cases} (2)
\]

4.1.3. Core damage degree. In considering the potential effects of radiological safety, in addition to considering radioactive release characteristics, the damage characteristics of the radioactive control barrier also need to be considered. According to INES standards, if more than 1% of the fuel in the reactor melts or the core releases more than 1% of the total radioactive material, the minimum should be level 5; if the core releases more than 0.1% of the total radioactive material, the minimum should be level 4. Assuming that the ratio of the amount of radioactive material released from the core of the marine reactor to the total amount of radioactive material in the core is \( Q_{reactor} \), and the rating given by the core damage is \( S_{reactor} \). The classification criteria for core damage characteristics under marine reactor accidents can be obtained, as shown in Equation 3.

\[
S_{reactor} = \begin{cases} 
5d(Q_{reactor} > 1\%) \\
4d(1\% > Q_{reactor} > 0.1\%) 
\end{cases} (3)
\]

4.1.4. Dose rate of work area radiation. The cabin radiation monitoring system for marine nuclear power plants provides powerful data support for operators to grasp the radiation exposure of the work area. Most of the measurement parameters of the radiation monitoring system are set with "alarm value" and "intervention value". If the measured value of a certain parameter exceeds its alarm value, it indicates that the radioactive capacity of the nuclear power device has defects in a certain aspect. In this situation, the lowest level of the event should be level 1. If the measured value of a parameter exceeds its intervention value, the operating personnel must take corresponding intervention measures, and the lowest level of the event should be level 2.

Assume that \( V_I \) is the measured value of a parameter in the radiation monitoring system, \( V_I^o \) is the alarm value of a parameter in the radiation monitoring system, and \( V_I^i \) is the intervention value of a parameter in the radiation monitoring system. Considering the radiation dose rate of the working area, the level is \( S_{region} \). The rating standard of the radiation dose rate in the working area under the marine reactor accident can be obtained, as shown in Equation 4.
\[ S_{\text{region}} = \begin{cases} 2(V_i > V'_i) \\ I(V'_i < V_i < V''_i) \end{cases} \]  

(4)

The event level \( S_{Ra} \) given in accordance with the “radioactive safety” guidelines shall be the maximum of the above four levels, namely:

\[ S_{Ra} = \max \left[ S_{\text{environment}}, S_{\text{person}}, S_{\text{reactor}}, S_{\text{region}} \right] \]

(5)

4.2. Evaluation criteria of in-depth defense capability impact

From the perspective of nuclear security defense, the factors affecting the assessment of nuclear safety incidents are: the expected frequency of initiating events, the operability of nuclear safety functions, and whether to challenge the basic safety functions of nuclear power plants.

4.2.1. Expected frequency of initiating events. According to the American Standards Institute's rating method, nuclear reactor accidents that have potential impact on safety mainly include expected events (frequency of occurrence \( f > 10^{-2}/\text{year} \)), rare events (frequency of occurrence \( f > 10^{-4}/\text{year} \) and \( f < 10^{-2}/\text{year} \)), and extreme accidents (which are unlikely to occur, \( f < 10^{-4}/\text{year} \)). If \( K \) is used to indicate the frequency of the originating event, then

\[ K_f = \begin{cases} K_1, (f > 10^{-2}) \\ K_2, (10^{-4} < f < 10^{-2}) \\ K_3, (f < 10^{-4}) \end{cases} \]

(6)

4.2.2. The operability of nuclear safety functions. In order to clearly evaluate the impact of an event on the operability of nuclear safety functions, in this paper we divides its potential impact into four categories: 1. fully meets the requirements, that is, all components that perform safety functions are intact, safety functions are not lost; 2. meets the minimum Operational limit requirements, that is, the operability of the safety system can maintain the reactor power operation, but the redundancy of the safety function may be lost; 3. the safety system is deeply affected, the basic safety function is affected, and the reactor cannot be operated. \( C \) is used to indicate the operability of the security function, then

\[ C = \begin{cases} C_1, (\text{Meet all the needs}) \\ C_2, (\text{Meet minimum operational needs}) \\ C_3, (\text{Meet the needs reluctantly}) \\ C_4, (\text{Cannot meet the needs}) \end{cases} \]

(7)

According to the INES rating standard, when the initial event poses a challenge to the basic safety function of the nuclear power plant, all combinations of the originating event frequency and the safety function operability can be represented by the rating matrix \( A_i \).

\[ A_i = \begin{bmatrix} C_1, C_2, C_3, C_4 \end{bmatrix} \begin{bmatrix} K_1, K_2, K_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 2 \\ 1.5 & 2.5 & 2.5 \\ 2.5 & 2.5 & 2.5 \\ 3 & 3 & 3 \end{bmatrix} \]

(8)
The value of each element in $A_1$ is the level of the event in the corresponding case, where the value of 1.5 indicates that the event can be set to either level 1 or level 2 in the same case; similarly, a value of 2.5 means that in this case, the event is set to level 2 and can also be set to level 3.

When the initiating event does not pose a challenge to the basic safety function of the nuclear power plant, all combinations of the frequency of potential initiating events requiring specific safety system actions and the safety function operability may be represented by a ranking matrix $A_2$.

$$A_2 = [C_1, C_2, C_3, C_4] \begin{bmatrix} K_1 & K_2 & K_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1.5 & 1 & 1 \\ 3 & 2 & 1 \end{bmatrix}$$

The value of each element in $A_2$ is the level of the event in the corresponding case, where a value of 1.5 indicates that the event can be set to either level 1 or level 2 in this case.

**4.2.3. Additional factors.** In some special cases, there may be additional factors that require the level of an event to be one level higher than the previous basic rating [5]. There are three main additional factors that meet this condition: common cause failures, safety culture issues, and inherent weaknesses in the device. Even if an event does not have any security significance in itself without considering these additional factors, it is possible to set it to level 1 because of these factors. Care should be taken when considering additional factors:

1. Considering all the additional factors, the level of the event can only be increased by one level.
2. The event level determined according to the “defense in depth” criteria cannot exceed level 3.

**4.3. Assessment standard of power output impact**

When the safety of the ship hull is threatened by external factors, it is very easy to damage the ship hull resulting in incalculable consequences if the power output ability of the nuclear power plant is completely lost. The situation may lead to multiple injuries or deaths, and ultimately affect nuclear safety. According to the rating scale of INES, the event level should be set as level 3; If the power output capacity of the nuclear power plant cannot fully meet the needs of tasks but can meet the power needs in an emergency, then the event level should be set as level 2. In this situation, the safety of the reactor can be guaranteed to a large extent, but the nuclear safety support capacity is reduced; If the nuclear power plant loses part of its power, but the remaining power output capacity can meet the needs of tasks and there is an external threat leading to the urgent and changeable situation, the ability of the ship to complete the follow-up tasks is threatened and the nuclear safety support ability is also affected, then the event rating should be set as level 1; When there is no external threat to the safety of the ship's hull, if the nuclear power plant completely loses the power output ability, the ability of the ship to complete the subsequent tasks will be affected to some extent, then the event rating should be set as 0.

It is assumed that the event level given in accordance with the "power output" criterion is $S_p$. Then $S_p$ can be expressed as:

$$S_p = \begin{cases} 4, & \text{(Complete loss of power in emergency situation)} \\ 3, & \text{(Emergency power needs can be met in emergency situation)} \\ 2, & \text{(Mission needs can be met in emergency situation)} \\ 1, & \text{(Complete loss of power in non-emergency situations)} \end{cases}$$

(10)
4.4. Rating procedure

Though the above analysis and evaluation criteria, referring to the rating method of INES, the rating table (as shown in Table 1) and rating procedure (as shown in Figure 1) of nuclear safety events of marine nuclear power plant can be determined.

![Rating procedure diagram](image-url)

**Figure. 1 Rating procedure**

**Table. 1 Nuclear event scale of marine nuclear power plant**

| Level | Radioactive safety | Defense in depth | Power output |
|-------|--------------------|-----------------|--------------|
| 7     | Environmental release exceeds the equivalent of $10^{16}$Bq$^{131}$I. | /               | /            |
| 6     | Environmental release exceeds the equivalent of $10^{15}$Bq$^{131}$I. | /               | /            |
| 5     | Environmental release exceeds the equivalent of $10^{14}$Bq$^{131}$I. | /               | /            |
| Event Rating | Description | Consequence |
|--------------|-------------|-------------|
| 4            | Environmental release exceeds the equivalent of $10^{13}$ Bq $^{131}$I. Fatal deterministic effects on individuals. More than 0.1% radioactive material in the core release. | The nuclear power plant is close to an accident and all safety measures fail. |
| 3            | Non-fatal deterministic effects on individual. The effective dose of a staff member exceeds 10 times of the whole body dose limit in a legal year. | In case of emergency, the power output capacity of nuclear power plant is completely lost. |
| 2            | An unprofessional member was exposed to more than 10 mSv. The dose of a staff member exceeds the limit in a legal year. The measured value of a parameter in the cabin radiation monitoring system exceeds the intervention value. | The safety measures are obviously invalid, but there is no actual consequence. |
| 1            | The dose of an unprofessional member exceeds the limit in a legal year. The dose of a staff member exceeds the dose limit value. The measured value of a parameter in the cabin radiation monitoring system exceeds the alarm value. | There are a few problems with safety components, but defense in depth is still effective. |
| 0            | No severity in safety. | In non-emergency situation, the power consumption of the whole ship cannot be fully guaranteed, and the output power of the turbo generator cannot meet the needs of the emergency power of the marine nuclear power plant. |

Before applying the nuclear safety event rating table of marine nuclear power plant to evaluate an event, it is necessary to determine whether the event has a potential impact on nuclear safety. If there is no impact on nuclear safety, the rating table cannot be used to evaluate the severity. If there is any impact on nuclear safety, firstly, the basic ratings of the event are given from three perspectives...
according to the criteria of "assessment standard of radioactive safety impact", "assessment standard of defense in depth capability impact" and "assessment standard of power output impact". Then the highest level of three ratings is selected as the final rating. Finally, the determined level should be checked for the consistency with the description in Tab.1. The rating should be determined again in case of any inconsistency.

5. Conclusion
The essence of nuclear safety event rating of marine nuclear power plant is to establish a unified rule system describing the relevant nature of the event (especially the importance of safety), so that a common understanding of the event can be got through brief communication information. The paper first describes the nuclear safety characteristics of marine nuclear power plant and discusses the basis for evaluating the severity of nuclear events of marine nuclear power plant in detail. Then the rating method is determined. The research results can provide strong support for the report and analysis of nuclear events, the feedback of nuclear power plant operational experience, and the nuclear emergency response of nuclear accidents. It is also of great significance for improving the operation safety support of marine nuclear power plant.

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