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Study of dose limits for crews on Nuclear-Powered ship from risk comparison between radiation and carcinogens

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1. Introduction

The International Maritime Organization (IMO) adopted a plan to reduce carbon by 2% per year from 2023 to 2026 at its 76th meeting and set a goal of reducing ship carbon emissions by 70% and greenhouse gas emissions by 50% by 2050 compared to 2008. The maritime sector is at a pivotal juncture, with major powers like China, the United States, and the United Kingdom initiating the development of nuclear-powered ships. This move, driven by the urgent need for sustainable and efficient transportation solutions, marks a significant step towards reducing the environmental impact of global shipping. Safety of Life At Sea (SOLAS) Chapter 8 “Nuclear powered ships” stipulate basic requirements for ships using nuclear power, especially related to radiation risks [1]. These are detailed and comprehensive safety guidelines for nuclear merchant ships adopted at the IMO General Assembly in 1981. In 2022, the Maritime and Coast Guard Agency (MCA) regulations on radiation safety for nuclear-powered ships were developed and implemented in the UK [2]. It provides safety guidelines for nuclear powered ships based on IMO SOLAS. Through case studies, it assesses the effectiveness of MCA regulations in safeguarding maritime personnel and the environment from radiation hazards associated with nuclear-powered ships. However, there are no exact radiation shielding guidelines for crew members.

However, unlike onshore nuclear power plants, radiation shielding cannot be installed without volume constraints on ships due to limited space and loading capacity. Therefore, the installation of an optimized structure for radioactivity shielding is required. To this end, determining the allowable level of radioactivity has to be first considered. Therefore, this study aims to study the dose limitation of the ship crew so that a reasonable shielding design can be obtained. For this purpose, the authors would like to review the risk level that can be accommodated by the crew of nuclear propulsion ships and calculate the amount of radiation suitable for the risk level using the International Commission on Radiation Protection (ICRP) calculation model.

2. Methods and Results

2.1. Application

Since the current dose standards classify radiation workers and the public and apply dose limitation separately, it is necessary to review the classification of the crew members in a nuclear-powered ship first. The ICRP defines a radiation worker as "a person who is employed by an employer and is aware of the rights and obligations related to job radiation protection, whether full-time, part-time, or temporary [3]." In addition, the Nuclear Safety Act defines "a person who is exposed to or concerned with radiation, such as the use, handling, storage, storage, processing, discharging, disposition, transportation, and other management or decontamination of radioactive materials [4]."

In accordance with the ICRP and the Nuclear Safety Act, radiation workers are combined to mean "workers employed by employers and who have the potential to be exposed to radiation by recognizing the rights and obligations related to radiation protection." It is reasonable to define a crew member of a nuclear-powered ship who is employed by the shipowner and who is aware of the need for radiation protection and works in a place with a high possibility of radiation exposure as a radiation worker.

The crew of the nuclear-powered ship will have a different task and working area. Rather than applying the same dose, classifying according to the mission and working area will be able to manage the number of people efficiently. Ship work is largely divided into navigation, deck, and engine departments. The representative departments related to radiation exposure will be the engine departments. Unlike the engine departments, the rest of the departments are far from exposure, so it would be reasonable to set a dose limit by dividing them into general crew members.

2.1.1 Engine crew risk criteria

Since the engine crew mainly performs their duties in the engine room near the reactor, there is a high possibility of exposure to relatively high doses of radiation. Therefore, it is reasonable to compare the risk levels with radiation exposure workers.

First, 'workers working in nuclear power plants' are subject to the annual dose limit of 20 mSv recommended by the ICRP. The standard set the risk exposure induced cancer death (REID) as 10^{-3}[5]. Therefore, assuming that the annual REID is considered 10^{-3} and that they work in a power plant for 46 years from age 18 to 64, the lifetime REID is calculated as 4.6×10^{-2} (4.6%). In addition, when exposed to 20mSv for 46years, the total dose is approximately 1,000mSv. The ICRP calculated the risk of cancer death in adults (18 to 64years old) at 4.1% when exposed to 1,000mSv. Therefore, 4.1 to 4.6% were selected as acceptable levels.

Second, the radiation standard for astronauts can be applied. The dose limits of astronauts by country are shown in the following table. The total exposure dose was selected as a dose limit. Dose limits suitable for special workers were applied as a characteristic of performing for a period of no special mission. Canada, Europe, and Russia set the total dose of 1,000mSv as a dose limit by applying 5% lifetime REID, which is the risk level applied to nuclear power plant workers. On the other hand, Japan and the United States considered 3% lifetime REID as an acceptable risk level. In conclusion, the risk level applied to astronauts is 3-5% lifetime REID.

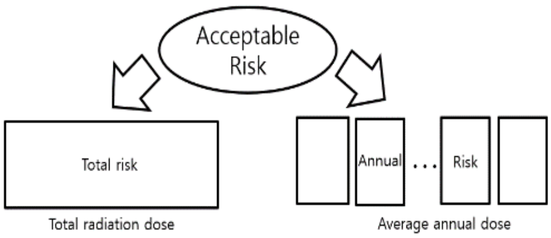

Figure. 1. Two type of dose limits

In this study, the authors will first explore what if nuclear powered ship workers in engine department are regulated with a dose standard set by the second method, which setting limit on the total exposure dose rather than annual dose. Therefore, a lifetime REID of 3% for crew members will be assumed to be the reference risk level.

2.1.2 General crew risk criteria

General crew members are crew members who work in areas spaced apart from nuclear reactors such as radars, communication equipment, and deck equipment. Therefore, it seems more reasonable to separate the risk level with carcinogens that can be easily exposed to general crew members than to compare the risk level with radiation exposure workers. In the case of general merchant ships using diesel engines, exposure to volatile organic compounds (VOCs) generated during combustion is typical. Among them, benzene, a first-class carcinogen, is a substance with a high risk of exposure to workers. Therefore, the radiation dose is evaluated based on the benzene management standards.

Among the benzene-related regulations, the work environment exposure standard of the Ministry of Employment and Labor in Korea is 3,000μg/m^3, and the exposure standard is set at 1,595μg/m^3 by the American Governmental Industrial Hygienists (ACGIH).

Therefore, it seems reasonable to approach conservatively and select the benzene exposure level as an excess carcinogenic risk level when the benzene exposure is 1,500μg/m^3.

To quantify the risk of exposure to benzene 1,500μg/m^3, the authors intend to use the 'Guidelines on the Procedure and Method for Assessing the Risk of Indoor Air Pollutants' under the Indoor Air Quality Control Act to assess the health risk caused by benzene inhalation [6]. This consists of four steps in the order of risk identification → dose-response evaluation → exposure evaluation → risk determination.

Risk identification evaluates the carcinogenicity of a substance and follows the carcinogenicity standards set by the U.S. Environmental Protection Agency (EPA) and the International Agency for Research on Cancer (IARC). Benzene is a carcinogen of 'Group 1' (Carcinogenic to human) in the IARC carcinogen class and 'A' (human carcinogen) in the EPA carcinogen class and is the highest level of carcinogen.

Dose-response evaluation is the step of determining the probability of side effects when the human body is exposed to a specific dose of harmful substances. The toxicity value of a carcinogen can be expressed as an Inhalation Unit Risk (IUR), which means the possibility of carcinogenesis when exposed to 1μg per 1m^3. IUR for all harmful substances is presented in the Office of Environmental Health Hazard Assessment (OEHHA) database, and benzene has an IUR of 2.9×10^{-5}[7]. The Cancer Potential Factor (CPF) can be calculated equation (1) using the IUR, which means the 95% upper limit of the probability of developing excess cancer that can occur when a healthy adult with an average weight lives in contact with an environmental medium contaminated with a chemical of a unit exposure(mg/kg/day) throughout his or her life. The CPF for benzene is 1.3×10^{-1}.

$$CPF(mg/kg/day)^{-1} = \frac{Inhalation\ Unit\ risk(\mu g/m^3)\times BW(kg)}{IR(m^3/day)} \times 1000(\mu g/m^3) \quad (1)$$

Exposure assessment is a step to evaluate how much exposure to substances identified as harmful and is expressed as Life Average Daily Dose (LADD) and calculated with Equation (2). 'C' is benzene concentration (mg/m^3), 'IR' is respiration rate (m^3/day), 'EF' is exposure day, 'ED' is exposure year, 'BW' is average weight (kg), and 'LT' is average life expectancy. Exposure scenarios were assumed for exposure assessment, and the subjects were general crew members, specifically, adult males aged 20 to 50 years (average weight of 70.6 kg, respiration rate of 15.6 m^3/day, 81 years) were assumed to be on board a ship for 30 years.

$$E_{inh}(mg/kg/day) = \sum_{i=m}^{n} \frac{(C \times IR \times EF \times ED)}{BW \times LT} \quad (2)$$

Risk determination is a final step in determining the risk of carcinogenesis by synthesizing information calculated from dose-response evaluation and exposure evaluation and is expressed as the product of CPF and LADD. As a result of calculating the risk of exposure to 1.5 mg/m^3 benzene of the crew as follows, the risk at the level of 1.07×10^{-2} (1%) is calculated. In general, the benzene-induced cancer type is known as leukemia (blood cancer). Therefore, REID can be calculated by reflecting the mortality rate (0.67) of leukemia (blood cancer) [8]. That is, the reasonable risk level that a general crew member who mainly performs tasks related to general ship operation in areas spaced apart from nuclear reactors is 0.7% of a lifetime REID.

2.2 Radiation Hazard

The risk level applicable to engine crew members was determined as lifetime REID 3%, and general crew members were determined as lifetime REID 0.7%. Therefore, a radiation dose with a corresponding risk can be considered as a reasonably acceptable dose. To calculate the risk of cancer due to radiation, a model made by ICRP was used. To evaluate the risk of cancer due to radiation exposure, a risk model for esophagus, stomach, colon, liver, lung, female breast, ovaries, bladder, thyroid gland, and bone marrow (leukemia) was used, and a nominal risk assessment of ICRP 60 (1991) was used because a risk model for bone or skin cancer was not established. Cancer from other tissues was assigned into residual categories called 'other solid cancers'. In addition, Excess Relative Risk (ERR) and Excess Absolute Risk (EAR) weighted averages of lifetime risk assessments were calculated by modeling ERR and EAR.

There are several ways to indicate lifetime risk for people who develop a specific disease and die from it, but the lifetime risk used in this study is the Risk of Exposure Induced Cancer (REIC), and when dose ‘d’ is exposed to exposure age ‘e’, the REIC of cancer type ‘c’ for reaching age ‘a’ is expressed as Equation (3).

$$REIC_c = \int_{e+L}^{T} [\mu_{ic}(a, e, d) - \mu_{ic}(a)] S(a, d|e) da \quad (3)$$

In Equation (3), ‘T’ is the average life expectancy, ‘L’ is the minimum incubation period, and the average life expectancy is 81 years, and the incubation period is 5 years for all types of cancer. The natural cancer incidence rate was reflected based on the number of cancer patients by KOSIS carcinoma/gender/age. ‘S(a,d|e)’ refers to the conditional probability that a person who survives at age ‘e’ will survive to age ‘a’ when a dose ‘d’ is exposed at age ‘e’. ‘μ_{ic}(a,e,d)’ represents the incidence of cancer in cancer type ‘c’ at age a after exposure to dose ‘d’ at age ‘e’

Therefore, if the reaching age is a discrete variable, it changes as shown in Equation (4) for the ERR model and Equation (5) for the EAR model.

$$REIC_{ERR}(e, d) = \sum_{n=e+L}^{T} ERR_{ic}(n, e, d) \mu_{ic}(n) S(n, d|e) \quad (4)$$

$$REIC_{EAR}(e, d) = \sum_{n=e+L}^{T} EAR_{ic}(n, e, d)\, \mathrm{S(n, d|e)} \quad (5)$$

The excess relative risk of developing cancer at age ‘a’ when exposed to dose ‘d’ at age ‘e’, and the model for solid cancer are shown in Equation (6). Custom variables and the variables for each type of cancer are shown in ICRP-152.

$$ERR_{ic} = \beta \times d \times \exp\left[\alpha_1 \left(\frac{e-30}{10}\right) + \alpha_2 \ln\left(\frac{a}{70}\right)\right] \quad (6)$$

The model of solid cancer is shown in (6), as the excess absolute risk of developing cancer at age ‘a’ when exposed to dose ‘d’ at age ‘e’. Currently, ‘α_1’, ‘α_2’, ‘β’ is a custom variable, and the variables for each type of cancer are shown in ICRP-152.

$$EAR_{il} = (\beta d + 1.53 d^2) \left(\frac{t}{25}\right)^a \quad (7)$$

EAR for leukemia is shown in Equation (7) and customized variables are shown in ICRP-152. In the case of leukemia, instead of using the ERR model, it was calculated by considering the EAR ratio to the incidence of natural cancer in the age of arrival and exposure.

In addition, since the calculation results by this model are risk calculation models based on the epidemiological data of high-dose rate and high-dose exposure subjects, correction of the result values is necessary to calculate the exposure of low-dose rate and low-dose radiation exposure. The ICRP recommended applying the dose rate effect factor (DDREF, Dose and Dose Rate Effectiveness Factor) 2 to doses less than 0.2 Sv. Therefore, in this study, the result value was calculated by dividing the correction factor 2 into the result value.

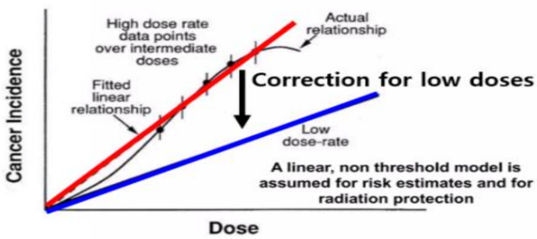

Figure. 2. Dose and dose rate effectiveness factor (DDREF)

Using the ICRP radiation risk model, the risk of exposure induced cancer incidence (REIC) for a dose of 100mSv was calculated by applying the probability of natural cancer incidence and survival probability based on Korean adult men. In addition, the risk exposure induced cancer death (REID) was calculated by applying the mortality rate for each carcinoma. Mortality values were applied based on two datasets of the US SEER program (5-year survival rate from 1980 to 1985 and 20-year survival rate from 1950 to 1970). [9]

Table 1: Radiation detriment calculation results by exposure age

Cancer site	20s REID	30s REID	40s REID
Total	3.6×10^{-3}	3.1×10^{-3}	2.7×10^{-3}

As shown in Table 1, REID according to radiation exposure varies according to the age of exposure, and the lower the exposure age, the higher the REID. Specifically, the REID for 100mSv exposure at 24 years old is calculated as 0.36%, the REID for 100mSv exposure at 34 years old is calculated as 0.31%, and the REID for 100mSv exposure at 44 years old is 0.27%. In addition, since it is assumed that the relationship between the dose and the REID is linear, it is possible to calculate the REID for a high dose based on Table 1, and the results are shown in Table 2.

Table 2: Radiation detriment calculation results by exposure dose

-	200 mSv	300 mSv	700 mSv	800 mSv	900 mSv
20s	0.72%	1.08%	2.52%	2.88%	3.24%
30s	0.61%	0.92%	2.16%	2.47%	2.77%
40s	0.55%	0.82%	1.92%	2.20%	2.47%

3. CONCLUSIONS

This study investigated dose limits that could reasonably be applied to nuclear-powered ship crews for effective radiation shielding design.

First, the classification of ship crew and whether the same dose should be applied were reviewed by observing related regulations. As a result of the review, it was confirmed that it is reasonable to consider ship crews as radiation workers and that it is desirable to apply different doses by dividing them into ‘engine crews’ and ‘general crews’ with different missions and work locations.

Since the effects of low-dose radiation follow the law of probability, the concept of risk that follows the same law of probability was applied to analyze the risks faced by engine crews and general crews. The radiation dose corresponding to the risk was calculated and recommended to apply as a dose limit.

Engine crews are workers who work directly related to nuclear reactors, and the risks faced by people exposed to radiation, such as nuclear power plant workers or astronauts, were used as a reference for developing dose limits for engine crews. For general crews, the risk of benzene that can be encountered in the working environment was used as a standard. As a result, the lifetime REID for engine crews was calculated to be 3%, and for general crews, the lifetime REID was calculated to be 0.7%.

The ICRP calculation model was used to calculate the radiation dose corresponding to the risk, and the data of Korean adult males were used for the calculation. As a result, as shown in Table 2, the REID for 100 mSv radiation exposure at age 20s was 0.36%, the REID for 100 mSv radiation exposure at 30s was 0.31%, and the REID for 100 mSv radiation exposure at 40s was 0.27%.

Based on these results, the radiation dose corresponding to REID 3%, which is the risk standard for engine crew members, is estimated to be in the range of 840 to 1000mSv. Additionally, the radiation dose corresponding to REID 0.7%, which is the risk standard for general crew members, is estimated to be in the range of 200 to 280mSv.

Due to the following results, it became possible to protect general crew members from excessive exposure by establishing separate dose limits. For engine crew members, it was possible to reduce the risk by more than 1% compared to the risk applied by the existing dose limit. In addition, since the total dose is presented instead of the annual dose, ship crews, who require considerable effort to train, can perform tasks more flexibly.

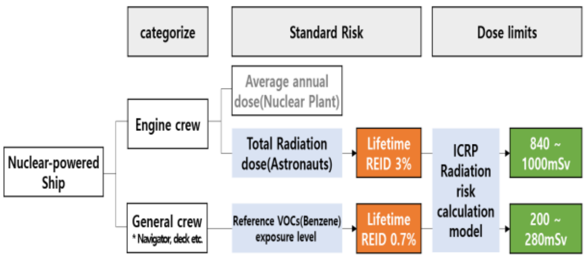

Figure. 3. Conclusions on limiting the dose to the crew of Nuclear-powered ships

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