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Study of dose limit for crews on Nuclear-Powered Civilian Underwater Vessel from risk comparison between radiation and carcinogens

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1. Introduction

Today, the world is trying to achieve carbon neutrality to avoid climate crisis. Among many energy sources available to humans, nuclear energy continues to attract attention as an irreplaceable energy not only in the present but also in the future. One of the possible applications of nuclear energy, nuclear-powered ships can become more important transportation option. A nuclear-powered ship is an overwhelmingly less carbon emitting vessel than conventional fossil-fueled ships. In particular, a nuclear-powered submarine to carry hydro-carbon fuels was proposed in the past and this vessel does not need to resurface for propulsion which becomes an ideal transportation for the arctic area [1].

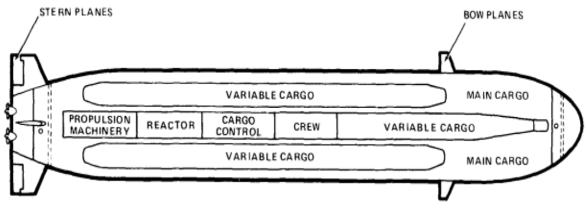

Fig. 1 Nuclear powered Submarine oil Tanker [1]

However, in the nuclear fission reaction, fissile material with high energy as well as neutrons and ionizing radiation are produced. Since ionizing radiation can have negative health effect to humans, radiation protection measures must be taken to protect the crew.

Nuclear-powered ships and submarines have space restrictions for shielding, and there is a load limit of the shielding system due to limited loading capacity. Thus, overly conservative approach to radiation protection in maritime vessel is not practical, and therefore it is necessary to establish a reasonable dose limit for the crew. However, dose limits for this type of system are not well established due to the characteristic of the reactor platform, which did not exist before, and there are questions about whether the dose limit standard used in land-based nuclear power plants should be used similarly in this case.

Therefore, this study aims to establish a dose limit for crew members of a underwater nuclear propelled cargo vessel in consideration of the space limitations. To this end, the applicability of the existing radiation dose limit standards is evaluated and the carcinogenic risk of maritime vessel platforms using diesel engines prior to nuclear power propulsion is compared to calculate the dose limits having equivalent risk to existing carcinogens.

2. Review of existing dose limits

2.1 Criteria for dose limits

Since the effect of radiation on the human body is studied widely, many radiation experts have calculated appropriate dose limits through the relationship between radiation dose and response to our body. After Roentgen discovered X-ray in 1895, the first dose limit was set to 150mSv, which is quite high compared to today's standards [2]. However, the dose limit has undergone a continuous revision process as research revealed more information on radiation. In particular, the International Commission on Radiation Protection established the standards for dose limits based on epidemiological data on the victims of atomic bomb in Japan. As a result, ICRP Report 103 (2007) proposed the dose limit of 100mSv for 5years (cannot exceed 50 mSv per year) for occupational exposure for radiation workers and 1 mSv for the general public per year [4]. Reflecting these ICRP recommendations, all radiation-related regulatory agencies, including nuclear power plants, are currently applying the corresponding standards.

Table. 1. The dose limits [4]

Type of limit	Occupational	Public
Effective dose	20 mSv/year, averaged over defined period of 5 years	1 mSv in a year
Annual equivalent dose limits		
Lens of the eye (mSv/year)	150	15
Skin (averaged over 1 cm^2) (mSv/year)	500	50
Hands and feet (mSv/year)	500	-
Pregnant women	1 mSv to the embryo/foetus till child birth	-

However, there are the following questions for the ICRP recommendation when it is applied to a underwater cargo vessel, which is in a special environment.

1. Should the crew be considered as radiation workers?

2. Should all crew members be regulated by the same dose limit?

3. What should be the practical dose limits?

2.2 Should the crew be considered as radiation workers?

First of all, it is necessary to review whether the occupational exposure standards apply to crew members on the underwater cargo vessels. Therefore, it is necessary to check the standards for radiation workers defined in the ICRP report and the Korean Nuclear Safety Act.

The ICRP defines a worker as a person employed by an employer, whether full-time, part-time or temporary, and aware of the rights and duties related to occupational radiological protection [4]. The law of the Republic of Korea defines a radiation worker as a person who is exposed to radiation or engages in work that is likely to be exposed to radiation, such as operation, maintenance of nuclear facilities, use, handling, storage, treatment, discharge, disposal, transportation, or other management or decontamination of radioactive materials [5].

Maritime vessel crew members are personnel hired by the state or private companies and work in areas with a high probability of being exposed to radiation, so it is desirable to consider them as radiation workers. Therefore, it seems reasonable that crew members of nuclear-powered underwater maritime vessel are subject to the occupational exposure standards.

2.3 Should all crew members be regulated by the same dose limit?

Obviously, even if they are members of the same submarine crew, their roles are different within the ship and thus the amount of radiation exposure will also be different. Therefore, it seems reasonable to apply different doses depending on the role and place of work even within the same vessel.

In particular, The ICRP notes that one of the important tasks of employers is to maintain control functions to control the sources of exposure and to protect occupationally exposed workers. To perform these functions, The ICRP recommends continuing to use work area classifications (Controlled areas and Supervised areas) [4]. Also, the law of the Republic of Korea divides workers into 'radiation workers' and 'Person with frequent access' and applies separate dose limits to each. Different dose standards are applied to them.

Table. 2. The republic of korea Nuclear Safety Act [6]

Division	Effective dose limits
Radiation worker	100 mSv for 5 years, not exceeding 50 mSv per year
Person with frequent access	6 mSv per year
Public	1 mSv per year

Both ICRP and Korean recommend and apply different doses limits by classifying them according to the roles and the work areas, even for the same worker. Therefore, it is reasonable to classify and apply dose limits to vessel crews according to their roles and places of work.

2.4 What should be the practical dose limits?

Crew members can be divided into engine crew members who work in the engine room close to the reactor room and general crew members who are not related to the reactor propulsion system and live in general living spaces. Thus, it is desirable for engine crew members to apply the occupational exposure standards directly recommended by the ICRP, taking into accounts the role of directly operating the reactor and the place of work near the reactor.

However, it is unreasonable to apply the same standard to general crew because general crew members are not directly related to the nuclear reactor and also work at a distance from the reactor. Also, they use maritime vessels as living spaces and it is possible to consider them as residents living near nuclear power plants.

The Korean Atomic Energy Act applies a dose limit of 6 mSv per year to frequent visitors who enter the radiation area for business purposes such as cleaning and facility management, except for temporary visits. However, it is not appropriate to simply regard general crew members as frequent visitors. Therefore, it is necessary to establish a dose limit for general crew members.

3. Criteria for general crew dose limits

Ultimately, the reason for establishing a dose limit is that excessive radiation poses health risk, such as cancer. However, radiation is not always harmful to our body. This is because the effect varies depending on the radiation dose and dose rate.

In general, the dose of threshold of deterministic effect that causes immediate effect is known to be 500mSv [7]. However, radiation from nuclear propulsion systems under normal operating conditions is attenuated by shielding and will be well below the threshold dose (500mSv) for deterministic effects. Therefore, the result of the radiation from the underwater vessel is not in deterministic region, but the probabilistic region for evaluating the risk, such as the probability of cancer occurrence.

Practically speaking, there is no place or occasion where the risk is zero. Especially the risk of cancer is common not only from radiation but also from other substances.

Therefore, it seems reasonable to calculate the dose limit for general crew members to have similar level of risk even though the propulsion system is converted from diesel to nuclear. In particular, a conventional naval submarine that operates with diesel engines for snorkeling in a small space have higher concentrations of carcinogens than a nuclear-powered submarine. Therefore, since diesel engines are not expected to operate in a nuclear-powered underwater cargo vessel, the risk of carcinogenicity will be lowered, and the reduced level will be able to be replaced with the radiation risk. It is noted that even though the main subject of this paper is a civilian underwater cargo vessel, the study will be referring to the regulations set by Korean navy, since it is only publicly accessible reference for this study.

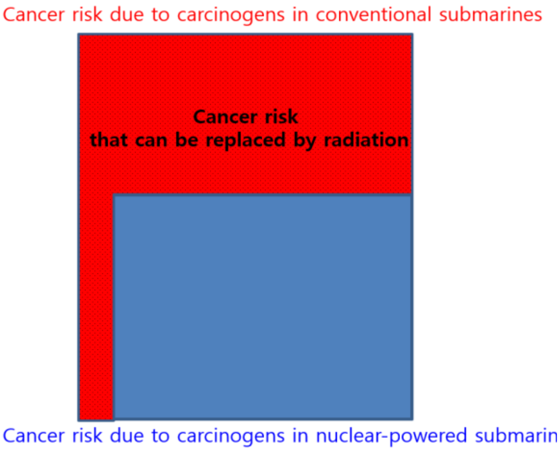

Fig. 2. Criteria for dose limits

4. Cancer risk due to carcinogens in conventional Submarines

4.1 Carcinogens in conventional submarines

In fact, the biggest difference between a conventional propulsion system and a nuclear propulsion system is whether or not the diesel engine is operating. Therefore, in the conventional propulsion method, the concentration of volatile organic compounds (VOC) generated during combustion of a diesel is inevitably high. Since the risk of VOCs are widely known, the Korean Navy, which operates conventional diesel submarines, has selected 4 types of VOCs (Benzene, Toluene, Ethylbenzene, Xylene) that are particularly harmful to the human body to protect crew members [8].

The carcinogenicity evaluation of harmful substances is mainly performed by the International Agency for Research on Cancer (IARC) and the United State Environment Protection Agency (US-EPA), and each agency evaluates carcinogenicity by dividing it into carcinogenicity levels. Of these, benzene has a high carcinogenic potential as Group 1 in IARC and Class A in EPA. On the other hand, ethylbenzene is not recognized as a carcinogen as Group 2B by IARC or Class D by EPA. Other substances are not recognized as carcinogens by either agency. Therefore, benzene is considered as the major carcinogen in this study, which will be compared with the radiation dose.

Table. 3. Carcinogenic classification [9, 10, 11]

IARC		US-EPA	
Group 1	Carcinogenic to human	A	Human carcinogen
Group 2A	Probably carcinogenic to human	B	Probable human carcinogen
		B1	Indicates limited human evidence
		B2	Indicates sufficient evidence in animal & inadequate or no evidence in human
Group 2B	Possible human carcinogen	C	Possible human carcinogen
Group 3	Not classifiable as to its carcinogenicity to human	D	Not classifiable as to human carcinogenicity
Group 4	Evidence of probably carcinogenicity to humans	E	Evidence of non-carcinogenicity for human

The Korean Navy not only selects harmful carcinogens, but also manages them at a similar level by referring to the management standards used in overseas submarines.

Table. 4. VOC Management and criteria [8]

Benzene		Criteria
International	US. ACGIH	1,595 $\mu g/m^3$
Submarine	US. SSBN	638 $\mu g/m^3$
	Canada.Victoria	1,500 $\mu g/m^3$
Toluene		**Criteria**
International	US. ACGIH	75,400 $\mu g/m^3$
Submarine	US. SSBN	75,400 $\mu g/m^3$
	Canada.Victoria	15,900 $\mu g/m^3$
Ethylbenzene		**Criteria**
International	US. ACGIH	86,708 $\mu g/m^3$
Submarine	Canada.Victoria	20,000 $\mu g/m^3$
Xylene		**Criteria**
International	US. ACGIH	434,192 $\mu g/m^3$
Submarine	US. SSBN	217,096 $\mu g/m^3$
	Canada.Victoria	17,800 $\mu g/m^3$

As shown in Table 1, it can be seen that the management standards for benzene in a nuclear-powered vessel are significantly lower than those in conventional submarines. This can be regarded as a natural phenomenon that occurs in a nuclear-powered vessel that does not operate diesel engines.

Therefore, the same level of radiation as the carcinogenic risk according to the decreasing concentration of benzene in a nuclear-powered vessel is regarded as an acceptable dose.

4.2 cancer risk calculation

In order to evaluate the health risks caused by inhalation of benzene, an evaluation method designed by the Indoor Air Quality Management Act of Korea is used. The guidelines for procedures and methods for risk assessment of pollutants in indoor air are used in this study [12].

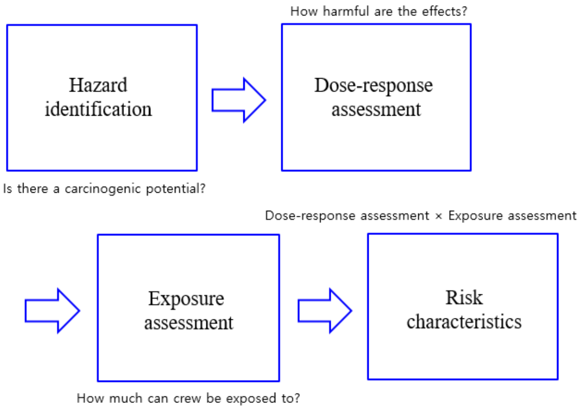

Fig. 3. Way of Evaluating the health risks caused by inhalation of carcinogens [12]

Hazard identification is a carcinogenicity evaluation, which can be performed with the EPA and IARC's carcinogenic criteria [9, 10, 11].

Dose-response evaluation is a step to determine the probability of adverse effects when the human body is exposed to a specific dose of a harmful substance. The toxicity value of a carcinogen is expressed as a Inhalation Unit Risk (IUR), which means the probability of carcinogenesis when exposed to 1 μg in 1m^3. The IUR is presented for all hazardous substances in OEHHA(Office of Environmental Health Hazard Assessment) chemical database meta data. The IUR of benzene is stated as 2.9×10^{-5}[12]

Cancer potency factor (CPF) can be calculated using IUR, and this value means the increased probability of cancer when exposed to 1 mg of harmful factors per 1 kg of body weight per day. CPF is the slope corresponding to the upper limit of 95% on the dose-response curve, that is, Slope factor. It means the upper limit of 95% of the excess cancer probability that can occur when a healthy adult of average weight lives in contact with an environmental medium contaminated with a unit exposure dose (mg/kg/day) of a chemical substance for a lifetime. The formula is as follows.

$$CPF(mg/kg/day)^{-1} = \frac{Inhalation\ Unit\ Risk(\mu g/m^3)\times 70.6kg}{15.6m^3/day}\times 1000\mu g/mg$$

Exposure assessment is the step of determining how much exposure is expected for a substance that has been identified as hazardous. The subject of the exposure evaluation was considered to be a navy petty officer, and in detail, an adult male between the ages of 24 and 53. The weight (70.6 kg), respiratory rate (15.6 m^3/day), and average lifespan (81 year) of the subject of evaluation were adopted as exposure factors for risk assessment of pollutants in the indoor air under the Indoor Air Quality Management Act of Korea [13]. The exposure period was 10 years, which is a typical submarine crew experience.

In addition, an exposure assessment was conducted to calculate Lifetime Average Daily Dose (LADD) through the formula below, and it was assumed that 100% of VOC exposed to the human body is absorbed.

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

- E_{inh} : Inhalation exposure of the diesel submarine (mg/kg/day)
- C : Inhalation exposure concentration of benzene (mg/m^3)
- IR : Average respiratory rate of the crew when boarding In submarine (m^3/day)
- EF : annual exposure frequency (days/yr)
- ED : Average period of use of the facility to be evaluated (years)
- BW : Average weight of the crew (kg)
- LT : Average lifetime of the crew (days)

As a result of calculating the crew member's excess cancer risk for Benzene in this way, the excess risk of 2.35×10^{-3} level was calculated.

Table. 5. Excess cancer risk by Benzene

VOC	CPF (mg/kg-day)$^{-1}$	Concentration (mg/m^3)	LADD (mg/kg-day)	Excess cancer risk
Benzene	1.31×10^{-1}	0.862	1.79×10^{-2}	2.35×10^{-3}

5. Cancer risk due to radiation.

The concept of radiation detriment, which quantifies the harm caused by radiation, was first introduced in 1973 in the ICRP 22 report. In particular, the probability of cancer caused by radiation was confirmed through a report from the Life Span Study (LSS) of Japanese Atomic Bomb Survivors Cohort. Therefore, ICRP developed a risk model to evaluate cancer risk based on the cancer data of atomic bomb survivors. Therefore, in this study, the model and methodology made by the ICRP were used to calculate the cancer risk due to radiation. However, the reference group was applied to Korean adult males between the ages of 24 and 53, the same as the carcinogen risk calculation.

5.1 Cancer detriment calculation methodology

For estimating the cancer risk from radiation exposure, ICRP developed risk models for esophagus, stomach, colon, liver, lung, female breast, ovary, bladder, thyroid, and leukemia. Risk models were not established for bone and skin cancers for which nominal risk estimates in ICRP 60(1991) were used. The cancers of other tissues were consigned to a remainder category called 'other solid cancers'. Also, ICRP modelled Excess relative risk (ERR) and excess absolute risk (EAR) to calculate the weighted average of the ERR and EAR lifetime risk estimates. Figure 9 summarizes basic information about cancer risk models used for the calculation of risk.

Table. 6. Cancer risk models for the calculation risk [15]

Organ/tissue	Source of information	Dose–risk relationship	ERR:EAR weights for risk transfer**
Oesophagus	LSS incidence†	L	50%ERR:50%EAR
Stomach	LSS incidence†	L	50%ERR:50%EAR
Colon	LSS incidence†	L	50%ERR:50%EAR
Liver	LSS incidence†	L	50%ERR:50%EAR
Lung	LSS incidence†	L	30%ERR:70%EAR
Bone	Nominal risk of *Publication 60*	L	100%EAR††
Skin*	Nominal risk of *Publication 59*	L	100%ERR‡‡
Female breast	Pooled analysis of eight cohorts‡	L	100%EAR
Ovary	LSS incidence†	L	50%ERR:50%EAR
Bladder	LSS incidence†	L	50%ERR:50%EAR
Thyroid	Pooled analysis of five cohorts§	L	100%ERR
Bone marrow	LSS incidence¶	LQ	50%ERR:50%EAR
Other solid	LSS incidence†	L	50%ERR:50%EAR

L, linear; LQ, linear-quadratic; ERR, excess relative risk; EAR, excess absolute risk; LSS, Life Span Study.
*Non-melanoma skin cancer.
†Solid cancer incidence in the LSS cohort for the period 1958–1998 (Preston et al., 2007).
‡Data from Preston et al. (2002).
§Data from Ron et al. (1995).
¶Leukaemia incidence in the LSS cohort for the period 1950–2000 (unpublished).
**See Section 3.1.4 for details on the transfer of risk estimates across populations.
††Nominal risk estimate using a constant absolute risk model was taken from *Publication 60* (ICRP, 1991).
‡‡Nominal risk estimate using a constant relative risk model was taken from *Publication 59* (ICRP, 1992).

Risk models involved a linear dose response allowing for modifying effects of sex, age at exposure, and attained age. Therefore, in this study, the risk was calculated by assuming a situation in which people aged 24 to 53 were exposed to radiation of 1 mSv per year after boarding a nuclear-powered submarine for 10 years during their 30-year naval life.

Among the methods to express the lifetime risk due to cancer, we intend to calculate it using Risk Exposure Induced Cancer Incidence (REIC). In the case of exposure age(e) and dose(d), the REIC of site(c) is as follows. At this time, T is the average age of 81, and L is the latency period.

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

In this equation, $\mu_{ic}(a,e,d)$ represents the cancer incidence rate at site(c)at age(a) after exposure to dose(d) at age(e) and $S(a,d|e)$ represents cancer-free survival is a conditional probability of surviving until age(a) without cancer for those who were alive at age(e).

The calculation method of $\mu_{ic}(a,e,d)$ for each ERR and EAR model is as follows.

$$\mu_{ic}(x,e,d) = \mu_{ic}(x)\big(1 + ERR_{ic}(x,e,d)\big)$$
$$\mu_{ic}(x,e,d) = \mu_{ic}(x) + EAR_{ic}(x,e,d)$$

ICRP devised a separate formula to calculate $ERR_{ic}(x,e,d)$ and $EAR_{ic}(x,e,d)$, and it is largely divided into solid cancer and leukemia. The model formula for solid cancer and the variable values for each model is as follows. The latency period was assumed to be 5 years.

$$\text{Excess risk} = \beta d \exp\left(\alpha_1 \frac{e-30}{10} + \alpha_2 \ln \frac{a}{70}\right)$$

Table. 7. The variable value for solid cancer EAR [15]

Cancer site	Sex	Excess cases per 10,000 persons per year per Gy at age 70 for exposure at age 30 (β)†	Parameter to allow for the change in EAR with age at exposure (α_1)†	Power of attained age by which EAR varies (α_2)†
All solid*	M	43.20	−0.27	2.38
	F	59.83		
Oesophagus	M	0.48	0.49	2.38
	F	0.66		
Stomach	M	6.63	−0.27	2.38
	F	9.18		
Colon	M	5.76	−0.27	2.38
	F	2.40		
Liver	M	4.18	−0.27	2.38
	F	1.30		
Lung	M	6.47	0.010	4.25
	F	8.97		
Breast	F	See Para. 38		
Ovary	F	1.47	−0.27	2.38
Bladder	M	2.00	−0.12	6.39
	F	2.77		
Other	M	7.55	−0.27	2.38
	F	10.45		

Table. 8. The variable value for solid cancer ERR [15]

Cancer site	Sex	ERR per Gy at age 70 for exposure at age 30 (β)†	Parameter to allow for the change in ERR with age at exposure (α_1)†	Power of attained age by which ERR varies (α_2)†
All solid*	M	0.35	−0.19	−1.65
	F	0.58		
Oesophagus	M	0.40	−0.19	−1.65
	F	0.65		
Stomach	M	0.23	−0.19	−1.65
	F	0.38		
Colon	M	0.68	−0.19	−1.65
	F	0.33		
Liver	M	0.25	−0.19	−1.65
	F	0.40		
Lung	M	0.29	0.16	−1.65
	F	1.36		
Ovary	F	0.32	−0.19	−1.65
Bladder	M	0.67	−0.19	−1.65
	F	1.10		
Thyroid	M	0.53	−0.82	0.00
	F	1.05		
Other solid	M	0.22	−0.42	−1.65
	F	0.17		

The EAR model formula for Leukemia and the variable values are as follows. The latency period was assumed to be 5 years. For leukemia, instead of using the ERR model, it was calculated by considering the EAR ratio for natural cancer incidence at the age of arrival and age of exposure.

$$\text{EAR per 10,000 persons per year} = (\beta d + 1.53 d^2)\left(\frac{t}{25}\right)^{\alpha}$$

Table. 9. The variable value for leukemia EAR model[15]

Sex	Age at exposure (years)	Coefficients for the linear-term of dose in Gy for time since exposure centred at 25 years (β)	Power of time since exposure by which EAR varies (α)
M	0–19	0.58	−1.54
	20–39	0.96	−0.69
	≥40	2.03	0.17
F	0–19	0.41	−1.06
	20–39	0.69	−0.21
	≥40	1.45	0.66

M, male; F, female.

In the following way, the REIC when exposed to 1 mSv per year for a total of 10 years, 1 year at 3-year intervals from the age of 24 to 53, is 7.41×10^{-4}. At this time, when DDREF 2 is applied, the REIC value is reduced by about half, finally reaching 3.7×10^{-4}

Table. 10. REIC calculation result by cancer site

Cancer site	Risk Exposure Induced Cancer Incidence (REIC)
Oesophagus	4.48×10^{-5}
Stomach	7.30×10^{-5}
Colon	1.29×10^{-4}
Liver	4.75×10^{-5}
Lung	2.15×10^{-4}
Bladder	1.67×10^{-5}
Thyroid	5.81×10^{-6}
Leukemia	4.60×10^{-5}
Bone	2.44×10^{-5}
Skin	4.15×10^{-5}
Other solid	9.69×10^{-5}
Total	7.41×10^{-4}
DDREF 2 applied	
Total	3.70×10^{-4}

6. Reasonable Consideration of Risk

In order to optimize the allowable dose in nuclear-powered underwater cargo vessel, the carcinogenic risk of benzene reduced in submarines was calculated by not operating diesel engines. To this end, the carcinogenic risk was calculated by calculating the difference between the benzene management standard for nuclear-powered submarines and conventional submarines. As a result, the carcinogenic risk caused by benzene is 2.35×10^{-3}

On the other hand, when the same exposure time is applied to the same reference group, the radiation risk caused by 1mSv is 3.7×10^{-4}, which is relatively low. Therefore, the radiation dose of the same level as the risk of cancer caused by benzene is 6.34mSv, and it can be considered that the radiation dose of about 6.5mSv does not exceed the existing risk.

In conclusion, the reduced risk obtained by converting to nuclear propulsion is 2.35×10^{-3}, and when it is replaced with radiation, it can be concluded that about 6.5mSv/year is an acceptable dose.

2.35×10^{-3} risk rate for 10 years can be expressed as 2.35×10^{-4} when converted to annual terms. Then, one can ask "is the annual cancer risk of 2.35×10^{-4} reasonably acceptable?" Regarding the degree of risk, it is not possible to suggest a specific reasonable level because the given situation is different and the degree of benefit obtained from risk is different. However, it is possible to confirm the level of acceptance by many people in general.

A report of a Study Group of the British Royal Society (1983) states that if individuals at risk are made aware of the situation and there is a significant benefit as a result, and understand that reasonable steps have been taken to reduce the risk, individuals judge that an annual probability of death of 1 in 1000 can be acceptable [3]. Travis et al. (1987a, 1987b) states cancer death probability above approximately 4×10^{-3} appeared to have been regulated regardless of cost [3]. ICRP states an annual occupational death probability of about 10^{-3} to the most exposed individuals would be at the border of being unacceptable [3].

Travis and Hattemeyer-Frey(1988) concluded that the range of 1×10^{-6} to 1×10^{-3}, are acceptable in modern society. The supreme Court action was instrumental in defining acceptable occupational risk. The court suggested that an occupational lifetime cancer risk of 1×10^{-3} is significant [16]. Also, EPA selected 3×10^{-3} because it was comparable to the working lifetime risk od accidental death in the least hazardous occupations [16].

As such, there are many views about risk, and in general, a risk level of 10^{-3} or less is reasonably acceptable. Therefore, it can be concluded that the annual risk of 6.5mSv/year for nuclear-powered civilian underwater cargo vessel exposure is reasonably acceptable.

7. Summary and Conclusion

Nuclear-powered civilian maritime vessels, which require no fuel supply on their way to the arctic area and do not emit harmful gases at high speed, are considered to be the means of transportation that will lead the future. However, a shielding structure is required to protect the crew, and it is required to establish a dose limit as a standard for shielding structure design. There is a dose limit previously used in nuclear power plants, but it is difficult to apply it as it is due to the nature of the maritime-vessel. Therefore, in this study, the authors intend to redefine the reasonable dose limit considering the characteristics of the maritime vessel.

Prior to the nuclear power propulsion system, a diesel engine-based propulsion system using charged batteries was used in navy. Since the diesel engine is operated in a narrow space, the concentration of volatile organic compounds, which are carcinogens, is high in conventional submarine. As a result, in conventional submarines, the risk of cancer caused by carcinogens is relatively high. It is noted that even though the subject of this study is a nuclear-powered civilian cargo vessel, since the underwater vessel is generally widely used in navy, the publicly accessible reference from navy is used for the study.

However, nuclear-powered maritime vessels no longer operate the diesel engines they used in the past. As a result, there is a risk reduction due to the reduction of carcinogens, and it seems reasonable to replace it with radiation at the reduced risk level. As a result, the excess cancer risk was calculated as 2.35×10^{-3}

On the other hand, when the same exposure time is applied to the same reference group, the radiation risk caused by 1mSv is 3.7×10^{-4}, which is relatively low level compared to carcinogens.

In conclusion, the radiation dose of the same level as the risk of cancer caused by benzene is 6.34 mSv, and it can be considered that the radiation dose of about 6 mSv does not exceed the existing risk. Also, there are many views on the acceptable level of risk. The previous studies show that a risk level of 10^{-3} or less is reasonably acceptable. Therefore, it can be concluded that the risk of 6.5mSv/year exposure for the general crew member onboard the nuclear-powered civilian underwater cargo vessel is reasonably acceptable.

REFERENCES

[1] Lawrence R. Jacobsen and James J. Murphy, Submarine Transportation of Hydrocarbons from the Arctic, Cold Regions Science and Technology, 7 273-283p, 1983
[2] ICRP Publication 1, 1959
[3] ICRP Publication 60, 1991
[4] ICRP Publication 103, 89p, 2007
[5] 원자력안전법 제 1 장 2 조 21 항, 2023
[6] 원자력안전법 시행령 제 1 장 2 조 4 항 별표 1, 2023
[7] ICRP Publication 147, 2019
[8] Naval Ship's Design/Shipbuilding Standards, "Criteria for Indoor Air Quality Control" Republic of Korea Navy,
[9] United States Environmental Protection Agency (US EPA), Lead and Compounds (Inorganic) (CASRN7439-92-1),
[10] International Agency for Research on Cancer (IARC), "Monographs on the Evaluation of Carcinogenic Risks to Humans, Inorganic and Organic Lead Compounds", 2006.
[11] United States Environmental Protection Agency (US EPA), "Risk assessment guidance for super fund volume, Human health evaluation manual (Part A)", 2004.
[12] OEHHA, Technical Support Document for Cancer Potency Factors, Appendix A, 2009
[13] 실내공기 중 오염물질의 위해성평가를 위한 절차와 방법 등에 관한 지침, 국립환경과학원고시 제2018-3호, 2018.
[14] Seong-Hwa Choi, Seong-Woo Choi, Dong-Yeong Kim, Young-Wook Cha, Seung-Woo Park,Seo-I Lee, and Eun-Chul Yoo, Evaluation of Health Risk from Concentrations of Heavy Metal in PM-10 and PM-2.5 particles at Sasang Industrial Complex of Busan, Journal of Environmental Analysis, Health and Toxicology Vol 24 133~148p. 2021
[15] ICRP Publication 103, 216-229p, 2022
[16] National Reserarch Council, Review of the Army's Technical Guides on Assessing and Managing Chemical Hazards to Deployed Personnel, Appendix B, 2004