Risk Comparison of Radiation to Carcinogenic Chemicals for Nuclear-Powered Maritime Vessels

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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]

However, radiation such as neutrons and gamma rays having high energy will be present in the vessel. Since exposure to such energy can adversely affect crew members, a shielding device to minimize health risk is essential.

However, nuclear-powered ships and submarines have space restrictions for shielding due to the characteristics of ships, and there is a load limit of the shielding system due to limited loading capacity. Since it is difficult to have an unlimited size of a shielding system, it is important to calculate an acceptable level of dose to the crew for effective shielding design for such nuclear-powered vessels.

Therefore, this study aims to study the acceptable level of dose in a submarine in order to have the effective shielding level. To do this, an excessive cancer risk due to the existing hazardous substances inside the conventional submarine (diesel-powered) is calculated and compared to the cancer risk due to radiation dose.

2. Hazardous substances and excess carcinogenic risk in diesel-powered vessel

2.1 Criteria for air quality

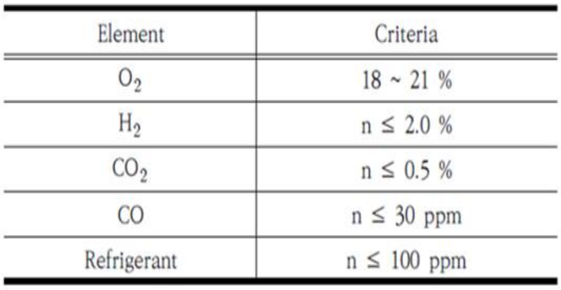
Since there is no diesel-powered commercial submarine for transporting hydro-carbon fuels from arctic area, this study will first refer to publicly available information on the S. Korean navy operating submarines. These diesel-powered submarines are typically smaller than nuclear-powered submarines and utilize diesel engines to recharge batteries.

The concentrations of carbon dioxide and fine dust are high because various equipment and many people live in a narrow and enclosed space. Furthermore, the concentration of Volatile Organic Compounds (VOC) is high because a diesel engine is operating in an enclosed space. Among various regulated substances, substances causing cancer are fine dust and VOCs.

Since the carcinogens in atmosphere are due to the special circumstances of thee diesel-powered submarines, the S. Korean navy stipulates the indoor air quality to be maintained above a certain level for the crew at the design stage. In addition, the concentration of pollutants is monitored in real time with a central gas monitoring system within the ship and is being managed.

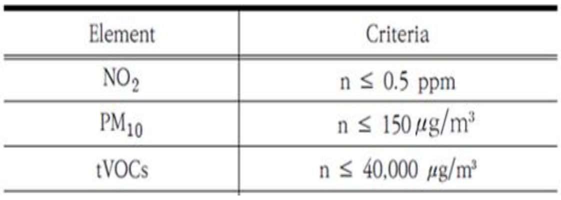
Table. 1. Criteria for air quality in conventional vessels [2]

(a) Constant Management Items



Element	Criteria
O_2	18 ~ 21 %
H_2	n ≤ 2.0 %
CO_2	n ≤ 0.5 %
CO	n ≤ 30 ppm
Refrigerant	n ≤ 100 ppm

(b) Tracking Management Items



Element	Criteria
NO_2	n ≤ 0.5 ppm
PM_{10}	n ≤ 150 $\mu g/m^3$
tVOCs	n ≤ 40,000 $\mu g/m^3$

2.2 Acceptable excess cancer risk levels in conventional submarines

Fine dust PM_{10} and Some of VOCs are classified as carcinogens in the submarine design/construction standards stipulated by the Navy. Since not all types of VOCs have a fatal effect on the human body, the Navy selected 4 VOCs having adverse health effects; benzene, toluene, ethylbenzene, and xylene. Among them, VOCs classified as carcinogens are Benzene and Ethylbenzene.

The S, Korean navy is currently referring to domestic civilian and international naval standards.[3] These standards are presented next. Since Canadian submarines are similar in size and displacement to Korean submarines, Canadian submarine standards are applied for the criteria of Korean submarines.

Table. 2. VOC Management and criteria [3]

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 $\mu g/m^3$

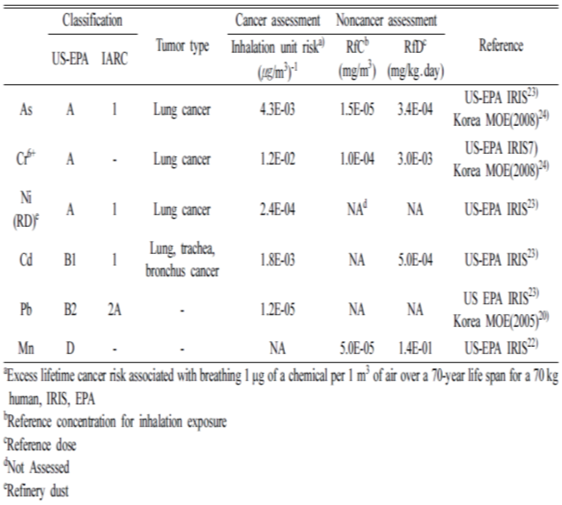
In other words, in order to maintain an acceptable risk level in a submarine, a certain limit value is set for each VOC and this value cannot be exceeded during operation.

Therefore, PM_{10} limit of 150 $\mu g/m^3$ and Canada Victoria submarines data of Benzene 1,500 $\mu g/m^3$ and Ethylbenzene 20,000 $\mu g/m^3$ are regarded as the safety standards to assess associated cancer risk.

2.3 Acceptable Excess cancer risk in diesel-powered submarines

2.3.1. PM_{10}

In general, inhalation of fine dust is known to be involved in the occurrence of respiratory-related diseases such as asthma, cardiovascular diseases, and reproductive-related abnormalities such as low birth weight and premature birth. In addition, the International Agency for Research on Cancer (IARC) recognizes that harmful heavy metals contained in atmospheric particulate matter can cause cancer. Therefore, in order to calculate the carcinogenic risk based on the level of fine dust, it is necessary to check the level of harmful carcinogenic heavy metals contained in fine dust. Representative carcinogenic and harmful heavy metals contained in fine dust are as follows.



	Classification		Tumor type	Cancer assessment	Noncancer assessment		Reference
	US-EPA	IARC		Inhalation unit risk[a] $(\mu g/m^3)^{-1}$	RfC[b] (mg/m^3)	RfD[c] (mg/kg.day)	
As	A	1	Lung cancer	4.3E-03	1.5E-05	3.4E-04	US-EPA IRIS[23)] Korea MOE(2008)[24)]
Cr^{6+}	A	-	Lung cancer	1.2E-02	1.0E-04	3.0E-03	US-EPA IRIS7) Korea MOE(2008)[24)]
Ni (RD)[f]	A	1	Lung cancer	2.4E-04	NA[d]	NA	US-EPA IRIS[23)]
Cd	B1	1	Lung, trachea, bronchus cancer	1.8E-03	NA	5.0E-04	US-EPA IRIS[23)]
Pb	B2	2A	-	1.2E-05	NA	NA	US EPA IRIS[23)] Korea MOE(2005)[20)]
Mn	D	-	-	NA	5.0E-05	1.4E-01	US-EPA IRIS[22)]

[a] Excess lifetime cancer risk associated with breathing 1 μg of a chemical per 1 m^3 of air over a 70-year life span for a 70 kg human, IRIS, EPA

[b] Reference concentration for inhalation exposure

[c] Reference dose

[d] Not Assessed

[e] Refinery dust

Fig. 1. carcinogenic and harmful heavy metals. [4]

However, since the standards managed by the Navy do not suggest figures related to harmful carcinogenic heavy metals in fine dust, specific cancer risk cannot be calculated, and it can be estimated with existing research data related to fine dust and carcinogenic risk.

According to the distribution of harmful heavy metal concentration and risk assessment in Busan industrial areas conducted by the Busan Institute of Health & Environment, the average PM10 level in industrial areas in Busan is 49 $\mu g/m^3$, which is 5.5×10^{-6} when the cancer risk is calculated.[4] Since the risk of cancer is proportional to the concentration of PM10, the risk of cancer with respect to the concentration of fine dust at the level of 150 $\mu g/m^3$, which is the atmospheric management standard in conventional submarines, is approximately 1.6×10^{-5}.

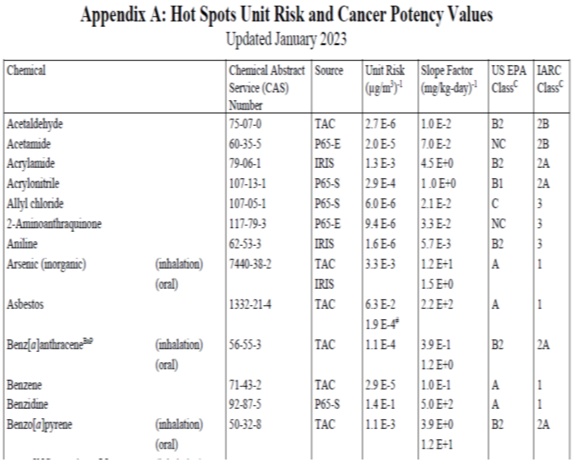
2.3.2. Volatile Organic Compounds (VOC)

In the case of VOCs, the Navy has specifically selected items, and since substances classified as carcinogens are defined, the excess carcinogenic risk can be calculated.

To calculate the cancer risk due to VOC, cancer potency factor (CPF) was calculated with Dose-response Assessment. Lifetime Average Daily Dose (LADD) was calculated with exposure assessment, and Excess Cancer risk was calculated by multiplying them together

Dose-response Assessment is a step in which the human body is exposed to a specific dose of a hazardous substance, how likely it will be adversely affected. In this study, the CPF presented by OEHHA

(Environmental Health Hazard Assessment) was applied. [5]



Appendix A: Hot Spots Unit Risk and Cancer Potency Values
Updated January 2023

Chemical		Chemical Abstract Service (CAS) Number	Source	Unit Risk $(\mu g/m^3)^{-1}$	Slope Factor $(mg/kg\text{-}day)^{-1}$	US EPA Class^C	IARC Class^C
Acetaldehyde		75-07-0	TAC	2.7 E-6	1.0 E-2	B2	2B
Acetamide		60-35-5	P65-E	2.0 E-5	7.0 E-2	NC	2B
Acrylamide		79-06-1	IRIS	1.3 E-3	4.5 E+0	B2	2A
Acrylonitrile		107-13-1	P65-S	2.9 E-4	1.0 E+0	B1	2A
Allyl chloride		107-05-1	P65-S	6.0 E-6	2.1 E-2	C	3
2-Aminoanthraquinone		117-79-3	P65-E	9.4 E-6	3.3 E-2	NC	3
Aniline		62-53-3	IRIS	1.6 E-6	5.7 E-3	B2	3
Arsenic (inorganic)	(inhalation)	7440-38-2	TAC	3.3 E-3	1.2 E+1	A	1
	(oral)		IRIS		1.5 E+0		
Asbestos		1332-21-4	TAC	6.3 E-2 1.9 E-4$^\#$	2.2 E+2	A	1
Benz[*a*]anthracene$^{B/P}$	(inhalation)	56-55-3	TAC	1.1 E-4	3.9 E-1	B2	2A
	(oral)				1.2 E+0		
Benzene		71-43-2	TAC	2.9 E-5	1.0 E-1	A	1
Benzidine		92-87-5	P65-S	1.4 E-1	5.0 E+2	A	1
Benzo[*a*]pyrene	(inhalation)	50-32-8	TAC	1.1 E-3	3.9 E+0	B2	2A
	(oral)				1.2 E+1		

Fig. 2. Cancer potency factors (OEHHA) [5]

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.

$$\mathrm{LADD(mg/kg/day)} = \frac{\mathrm{C\ mg/m^3 \times IR\ m^3/day \times EF\ \ day/year \times EP\ \ year}}{\mathrm{BW\ \ kg \times\ LT\ \ day}}$$

LADD: lifetime average daily doses
C: contaminant concentration in inhaled air
IR: inhalation rate(m^3/day)
EF: expose frequency(day/year)
EP: expose period(year)
BW: body weight(kg)
LT: lifetime(day)

Fig. 3. Formula of LADD

The subject was selected as an adult male between the ages of 20 and 53 who can represent the submarine crew, and the average weight of the age group of 73 kg and the average life span of 81 years were applied. The inhalation rate was the amount of air inhaled from breathing during the day, and an average of 13 m^3/day for adults was applied.

The exposure period was assumed to be 11.3 years by dividing the service period of 34 years by 3 by applying the Operation (1/3) - Train (1/3) – Rest (1/3) Cycle, a concept of power management of the Navy, among the 34 years of service for general Petty officers (Senior Sergeant rank).

As a result of calculating the crew member's excess cancer risk for VOC in this way, the excess risk of 8.07×10^{-3} level was calculated.

Table. 3. Excess cancer risk by VOC

VOC	Criteria (mg/m^3)	CPF $(mg/kg\text{-}day)^{-1}$	LADD (mg/kg-day)	Excess cancer risk
Benzene	1.5	1.0×10^{-1}	3.7×10^{-2}	3.73×10^{-3}
Ethyl benzene	20	8.7×10^{-3}	4.9×10^{-1}	4.34×10^{-3}
Total				8.07×10^{-3}

3. Excess cancer risk due to radiation

The calculation of the excess cancer risk due to radiation should consider the characteristics of the cancer. Cancer generally has a period in which the probability of cancer occurrence does not significantly increase even after radiation is irradiated. This period is called the Latent period, and the period of the latent period depends on the age of the individual exposed to radiation and the final location of the malignant tumor. After the latent period, a plateau period appears, where the risk of developing cancer is constant throughout the period. Therefore, the risk of cancer occurrence during the plateau period is calculated and called the Risk Coefficient, which is the expected number of cancer occurrences per year due to irradiation of 10^6 man-10mSv. [6]

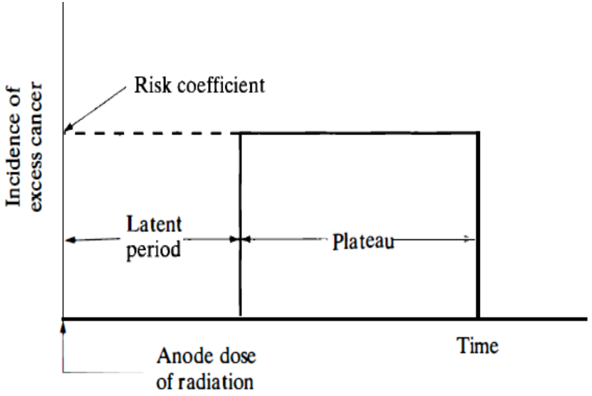
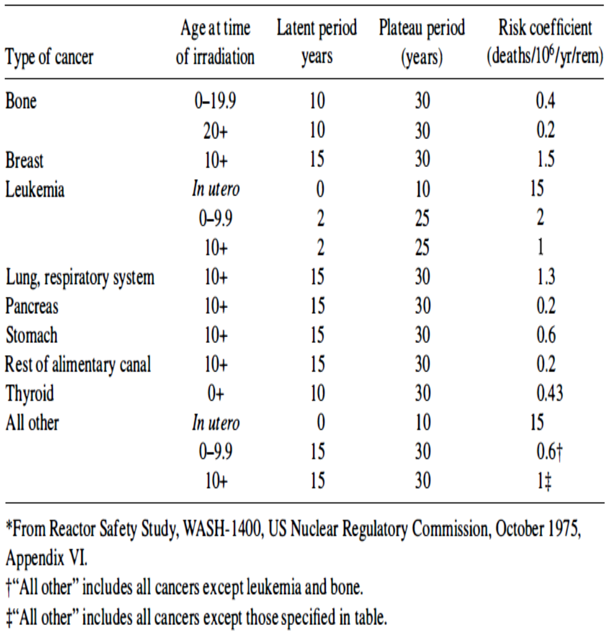


Fig. 4. Schematic diagram of cancer characteristics [6]



Type of cancer	Age at time of irradiation	Latent period years	Plateau period (years)	Risk coefficient (deaths/10⁶/yr/rem)
Bone	0–19.9	10	30	0.4
	20+	10	30	0.2
Breast	10+	15	30	1.5
Leukemia	*In utero*	0	10	15
	0–9.9	2	25	2
	10+	2	25	1
Lung, respiratory system	10+	15	30	1.3
Pancreas	10+	15	30	0.2
Stomach	10+	15	30	0.6
Rest of alimentary canal	10+	15	30	0.2
Thyroid	0+	10	30	0.43
All other	*In utero*	0	10	15
	0–9.9	15	30	0.6†
	10+	15	30	1‡

*From Reactor Safety Study, WASH-1400, US Nuclear Regulatory Commission, October 1975, Appendix VI.
†"All other" includes all cancers except leukemia and bone.
‡"All other" includes all cancers except those specified in table.

Fig. 5. Characteristics by cancer type [6]

Considering the characteristics of these cancers, the excess cancer risk is calculated as follows. Assuming that a 20-year-old adult male boarded a nuclear-powered hydro-carbon fuel carrier for the first time, was discharged at the age of 53, and was exposed to 20 the average occupational dose limit for 34 years, this is the probability of cancer occurrence within the average lifetime.

The proposed risk coefficient was applied considering the latent and plateau periods of cancer. For example, for leukemia, the latent period is 2 years, the plateau period is 25 years, and the risk coefficient is 1×10^{-6}. Therefore, a dose of 20 mSv exposed at the age of 20 causes an excess cancer risk for 25 years from the age of 22 to 46, excluding the incubation period. That is, 2rem (20mSv) × 1×10^{-6} (Risk coefficient) × 25 (plateau). Such exposure is expected to be received until the age of 53, and exposure received at the age of 53 in the same way causes an excess cancer risk from the age of 55 to 79, excluding the incubation period.

Therefore, the excess cancer risk of leukemia caused by 34 years of 20 mSv radiation exposure between the ages of 20 and 53 is 1.7×10^{-3}

[2rem(20mSv)$\times1\times10^{-6}$(Risk coefficient)$\times$25(plateau)$\times$34(exposure year)]

The excess cancer risk for each type of radiation-induced cancer is calculated using the same principle as follows.

Table. 4. Excess cancer risk of cancer type

Type of cancer	Latent	plateau	Risk coefficient	Excess cancer risk
Bone	10	30	0.2×10^{-6}	3.7×10^{-4}
Leukemia	2	25	1×10^{-6}	1.7×10^{-3}
Lung, respiratory system	15	30	1.3×10^{-6}	2.2×10^{-3}
Pancreas	15	30	0.2×10^{-6}	3.4×10^{-4}
Stomach	15	30	0.6×10^{-6}	1.0×10^{-3}
Rest of alimentary canal	15	30	0.2×10^{-6}	3.4×10^{-4}
Thyroid	10	30	0.43×10^{-6}	8.1×10^{-4}
All other	15	30	1×10^{-6}	1.7×10^{-3}
Total				7.56×10^{-3}

4. Summary and Conclusions

Considering the deterministic and stochastic effects of radiation, the goal of radiation protection becomes clear. It is to reduce the deterministic effect by making the allowable dose below the threshold dose and to minimize the stochastic effect by lowering the allowable dose as much as possible. However, considering the structural characteristics of the nuclear submarine's space and load limit, it is impossible to install an unlimited size of shield. Therefore, the stochastic effect cannot be ignored and efforts should be made to minimize it.

Therefore, this study is on what level of dose will be reasonable as an acceptable level in a submarine. To this end, the risk of cancer occurrence at the level currently accepted in conventional submarines was calculated.

Inside a conventional submarine, the concentration of carbon dioxide, fine dust, and volatile organic compounds are higher than in a typical living space. Among them, PM_{10}, Benzene, and Ethylbenzene, which have the potential to be carcinogenic, are designated as management targets and managed, and the standards for Canadian submarines are presented. Therefore, the proposed criterion was assumed to be the maximum acceptable risk, and the probability of cancer occurrence was calculated using this criterion, which is approximately 8.1×10^{-3}.

In order to calculate the excess cancer risk caused by radiation that is similar to the level of cancer risk caused by the atmosphere of a conventional submarine, the excess cancer risk at 20 mSv, the average dose of occupational exposure recommended by the ICRP, is approximately 7.56×10^{-3}.

Table. 5. Comparison of excess cancer risk

Type of substance		Excess cancer risk	
PM_{10} ($150\ \mu g/m^3$)	Total	1.6×10^{-5}	8.07×10^{-3}
Benzene ($1{,}500\ \mu g/m^3$)		3.73×10^{-3}	
Ethylbenzene ($20{,}000\ \mu g/m^3$)		4.34×10^{-3}	
Radiation (20mSv)		7.56×10^{-3}	

In conclusion, the acceptable level of excess cancer risk due to the special atmospheric conditions of conventional submarines corresponds to the cancer risk caused by the average occupational dose(20mSv). Therefore, it seems that the allowable radiation dose for crew members of future nuclear-powered submarines is reasonable to be the same with nuclear power industrial limit 20mSv for the moment. A radiation shielding system for radiation protection that can meet this level should be designed and installed.

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