Risk Comparison between Occupational and Military Radiation Dose Limits Standards

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1. Introduction

Radiation exposure is a critical concern in both occupational and military settings, where personnel may encounter ionizing radiation from various sources. In the civilian sectors, radiation workers operate under stringent regulatory frameworks designed to minimize exposure and associated health risks. Conversely, military personnel, particularly those involved in nuclear operations, submarine crews, and battlefield scenarios, often face unique exposure conditions where risk tolerances and permissible dose limits differ due to operational necessities.

To manage radiation exposure, both sectors adhere to fundamental radiological protection principles, such as the As Low As Reasonably Achievable (ALARA) approach. Nuclear power plants and medical institutions currently operating with radiation strictly adhere to the dose limitation recommendations outlined in the ICRP 60 report, and regulatory agencies also use these standards for regulation. In contrast, military radiation standards are influenced by mission requirements, sometimes allowing higher permissible doses, especially in emergency scenarios.

A key framework in military radiation management is the Operational Exposure Guide (OEG), which provides a structured approach to classifying and managing radiation exposure [1]. The Radiation Exposure Status (RES) Categories, outlined in Table I, define cumulative exposure levels for personnel and units, enabling commanders to assess mission risks and adjust strategies accordingly.

Table I. Radiation exposure status categories [1]

RES-0	The unit has not had any radiation exposure.
RES-1	The unit has been exposed to greater than 0cGy but less than or equal to 70cGy.
RES-2	The unit has been exposed to greater than 70cGy but less than or equal to 150cGy.
RES-3	The unit has been exposed to greater than 150cGy.

To further refine risk assessment, the OEG categorizes radiation risks into three levels: negligible, moderate, and emergency [1]. These risk levels define acceptable exposure limits and their potential effects on personnel, balancing mission objectives with radiation safety.

Table II. Risk classification for military [2]

Risk	Dose	Expected Casualties	Performance impact	Operational Acceptability
Negligible Risk (RES-0)	D ≤ 50	None	Minimal, Under 2.5% experience transient nausea or fatigue	Acceptable for prolonged operations in contaminated areas
Moderate Risk (RES-1)	D ≤ 70	Up to 5%	Minor, Under 5% experience temporary performance degradation	Acceptable for critical missions requiring sustained effectiveness
Emergency Risk (RES-2 ~ 3)	D ≤ 150	Up to 5%	Significant, Increased likelihood of radiation – induced symptoms, potential need for reassignment	Only acceptable in disaster scenarios where mission success outweighs radiation risks

This classification, outlined in Table II, enables military decision-makers to implement protective measures while maintaining operational effectiveness. Unlike civilian limits, which are strictly regulated to minimize occupational health risks, the OEG allows for situational flexibility, particularly in combat or emergency scenarios where increased exposure may be unavoidable.

This paper aims to evaluate risk levels by comparing the standards applied to individuals working in the nuclear industry with those used in the military. Additionally, radiation dose based on these standards will be calculated using the ICRP radiation risk calculation methodology.

2. Radiation risk calculation methodology

The lifetime risk used in the ICRP calculation model is the Risk of Exposure Induced Cancer incidence (REIC) [2]. When people were exposed to a dose (d) at the age (e), the REIC of cancer type (c) for the attained age (a) is expressed in equation (1).

$$REIC_c = \int_{e+L}^{T} [u_{ic}(a,e,d) - u_{ic}(a)] S(a,d|e) da \quad (1)$$

In equation (1), T is the average lifespan and L is the Latent period. $u_{ic}(a,e,d)$ represents the cancer incidence rate of cancer type (c) at age after exposure to dose (d) at age (e) $u_{ic}(a)$ means the natural cancer trigger rate. $S(a,d|e)$ means the conditional probability that a person alive at age (e) will survive to age (a) when exposed to dose (d) at age (e).

Risk models for the esophagus, stomach, colon, liver, lungs, female breast, ovaries, bladder, thyroid, and bone marrow (leukemia) were used to assess cancer risk from radiation exposure. However, since risk models for bone cancer and skin cancer have not been established, the nominal risk estimates from ICRP 60 (1991) were used. Cancers of other tissues were assigned to a residual category referred to as other solid cancers. Additionally, excess relative risk (ERR) and excess absolute risk (EAR) were modeled to calculate the weighted averages of ERR and EAR for lifetime risk estimates in Table III.

Table III. The risk models for each organ/tissue category [2]

Organ / tissue	Source of information	Dose-risk relationship	ERR: EAR Weights for risk transfer
Esophagus	**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	**Normal risk of Publication 60**	**L**	**100% EAR##**
Skin*	**Normal risk of Publication 59**	**L**	**100% ERR$$**
Female breast	**Pooled analysis of 8cohorts^**	**L**	**100% EAR**
Ovary	**LSS incidence#**	**L**	**50% ERR: 50% EAR**
Bladder	**LSS incidence#**	**L**	**50% ERR: 50% EAR**
Thyroid	**Pooled analysis of 5 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)
&Leukemia incidence in the LSS cohort for the period 1950-2000(unpublished)
##Nominal risk estimate using a constant absolute risk model was taken from Publication 60(ICRP, 1991)
$$Nominal risk estimate using a constant absolute risk model was taken from Publication 59(ICRP, 1992)

Absolute risk (AR) is the probability of disease occurrence during the period of radiation exposure. On the other hand, relative risk (RR) compares the risk of exposed group and the unexposed group. EAR is the additional risk of disease in an exposed group compared to an unexposed group. ERR is the proportional increase in risk in an exposed group compared to an unexposed group. The ERR model and EAR model can be represented as equations (2) and (3).

$$u_{ic}(a,e,d) = u_{ic}(a)(1 + ERR_{ic}(a,e,d)) \quad (2)$$
$$u_{ic}(a,e,d) = u_{ic}(a)(EAR_{ic}(a,e,d)) \quad (3)$$

By adapting each model into the REIC formula, each model was calculated as equations (4) and (5).

$$REIC_{ERR}(e,d) = \sum_{n=e+L}^{T} ERR_{ic}(n,e,d)\, u_{ic}(n) S(n,d|e) \quad (4)$$
$$REIC_{EAR}(e,d) = \sum_{n=e+L}^{T} EAR_{ic}(n,e,d)\, S(n,d|e) \quad (5)$$

$ERR_{ic}(a,e,d)$ and $EAR_{ic}(a,e,d)$ for solid cancer, exposure at age (e) with dose (d), leading to cancer occurrence at attained age (a), are defined by equation (6) and (7). (B), (a_1) and (a_2) are adjustment variables, while cancer-specific parameters are provided in Table IV and Table V.

$$ERR_{ic} = B \times d \times \exp\left[a_1\left(\frac{e-30}{10}\right) + a_2 \ln\left(\frac{a}{70}\right)\right] \quad (6)$$
$$EAR_{ic} = B \times d \times \exp\left[a_1\left(\frac{e-30}{10}\right) + a_2 \ln\left(\frac{a}{70}\right)\right] \quad (7)$$
$$EAR_{ic} = B \times d \times \exp\left[-0.5\left(\frac{e-30}{10}\right) + 3.5 \ln\left(\frac{a}{70}\right)\right] \quad (a \le 50) \quad (8)$$
$$B \times d \times \exp\left[-0.5\left(\frac{e-30}{10}\right) + 3.5 ln\left(\frac{a}{70}\right) - 2.5 \ln\left(\frac{a}{50}\right)\right] \quad (a > 50)$$

These models allow for a quantitative assessment of the impact of radiation exposure on cancer risk at a specific age.

Table IV. Parameters for the incidence-based ERR model [2]

Cancer site	ERR per Gy at age 70 for exposure at age 30 (B)	Parameter to allow for the change in ERR with age at exposure (a_1)	Power of attained age by which ERR varies (a_2)
All solid	**M: 0.35 / F: 0.58**	**-0.19**	**-1.65**
Esophagus	**M: 0.40 / F: 0.65**	**-0.19**	**-1.65**
Stomach	**M: 0.23 / F: 0.38**	**-0.19**	**-1.65**
Colon	**M: 0.68 / F: 0.33**	**-0.19**	**-1.65**
Liver	**M: 0.25 / F: 0.40**	**-0.19**	**-1.65**
Lung	**M: 0.29 / F: 1.36**	**0.16**	**-1.65**
Ovary	**F: 0.32**	**-0.19**	**-1.65**
Bladder	**M: 0.67 / F: 1.10**	**-0.19**	**-1.65**
Thyroid	**M: 0.53 / W: 1.05**	**-0.82**	**0.00**
Other Solid	**M: 0.22 / W: 0.17**	**-0.42**	**-1.65**

Table V. Parameters for the incidence-based EAR model [2]

Cancer site	Excess cases per 10,000 persons per year per Gy at age 70 for exposure at age 30 (B)	Parameter to allow for the change in EAR with age at exposure (a_1)	Power of attained age by which ERR varies (a_2)
All solid	**M: 43.35 / F: 59.83**	**-0.27**	**2.38**
Esophagus	**M: 0.48 / F: 0.66**	**0.49**	**2.38**
Stomach	**M: 6.63 / F:9.18**	**-0.27**	**2.38**
Colon	**M: 5.76 / F: 2.40**	**-0.27**	**2.38**
Liver	**M: 4.18 / F: 1.30**	**-0.27**	**2.38**
Lung	**M: 6.47 / F: 8.97**	**0.010**	**4.25**
Ovary	**F: 0.32**	**-0.27**	**2.38**
Bladder	**M: 0.67 / F: 1.10**	**-0.12**	**6.39**
Other Solid	**M: 0.22 / W: 0.17**	**-0.27**	**2.38**
Breast	*** Equation (8) /** B: 25.3		

3. Results and Discussion

Based on the ICRP model and the 2022 KOSIS statistics, the natural cancer incidence probability was applied to Korean adults to calculate the age-specific REIC for a radiation dose of 100 mSv [3]. The cancer-fatality rates were determined using the U.S. SEER program to calculate the REID (Risk Exposure Induced Cancer Death) [2]. The calculated values for adult males and females are presented in Table VI and Table VII. Since the ICRP model assumes linearity, the REID calculations for radiation exposure levels corresponding to the RES criteria are provided in Table VIII.

Table VI. Radiation detriment results for adult males

Cancer site	Fatality rate	In 20s (exposed at 24)		In 30s (exposed at 24)		In 40s (exposed at 24)	
		REIC	REID	REIC	REID	REIC	REID
Esophagus	0.93	3.3×10^{-4}	3.1×10^{-4}	3.0×10^{-4}	2.7×10^{-4}	2.7×10^{-4}	2.5×10^{-4}
Stomach	0.83	6.0×10^{-4}	5.0×10^{-4}	4.4×10^{-4}	3.6×10^{-4}	3.0×10^{-4}	2.5×10^{-4}
Colon	0.48	5.6×10^{-4}	2.7×10^{-4}	4.1×10^{-4}	2.0×10^{-4}	2.8×10^{-4}	1.4×10^{-4}
Liver	0.95	4.0×10^{-4}	3.8×10^{-4}	2.9×10^{-4}	2.8×10^{-4}	2.0×10^{-4}	1.9×10^{-4}
Lung	0.89	6.1×10^{-4}	5.5×10^{-4}	6.1×10^{-4}	5.5×10^{-4}	5.9×10^{-4}	5.3×10^{-4}
Bladder	0.29	1.8×10^{-4}	5.1×10^{-5}	1.4×10^{-4}	3.9×10^{-5}	1.0×10^{-4}	3.0×10^{-5}
Thyroid	0.07	4.2×10^{-5}	3.0×10^{-6}	1.5×10^{-5}	1.1×10^{-6}	4.5×10^{-6}	3.2×10^{-7}
Leukemia	0.67	1.7×10^{-3}	1.1×10^{-3}	9.9×10^{-4}	6.6×10^{-4}	8.5×10^{-4}	5.7×10^{-4}
Bone	0.45	1.7×10^{-6}	7.4×10^{-7}	1.3×10^{-6}	6.0×10^{-7}	1.0×10^{-6}	4.5×10^{-7}
Skin	0.002	2.4×10^{-4}	4.7×10^{-7}	2.3×10^{-4}	4.7×10^{-7}	2.3×10^{-4}	4.5×10^{-7}
Other	0.49	5.8×10^{-4}	2.8×10^{-4}	4.8×10^{-4}	2.3×10^{-4}	3.7×10^{-4}	1.8×10^{-4}
Total			3.5×10^{-3}		2.6×10^{-3}		2.1×10^{-3}

Table VII. Radiation detriment results for adult females

Cancer site	Fatality rate	In 20s (exposed at 24)		In 30s (exposed at 24)		In 40s (exposed at 24)	
		REIC	REID	REIC	REID	REIC	REID
Esophagus	0.93	1.0×10^{-4}	9.4×10^{-5}	1.2×10^{-4}	1.1×10^{-4}	1.5×10^{-4}	1.4×10^{-4}
Stomach	0.83	8.2×10^{-4}	6.8×10^{-4}	5.9×10^{-4}	4.9×10^{-4}	4.1×10^{-4}	3.4×10^{-4}
Colon	0.48	2.4×10^{-4}	1.1×10^{-4}	1.7×10^{-4}	8.3×10^{-5}	1.2×10^{-4}	5.7×10^{-5}
Liver	0.95	1.3×10^{-4}	1.2×10^{-4}	9.5×10^{-5}	9.0×10^{-5}	6.5×10^{-5}	6.2×10^{-5}
Lung	0.89	8.9×10^{-4}	7.9×10^{-4}	8.9×10^{-4}	7.9×10^{-4}	8.6×10^{-4}	7.6×10^{-4}
Bladder	0.29	2.2×10^{-4}	6.3×10^{-5}	1.9×10^{-4}	5.6×10^{-5}	1.7×10^{-4}	4.9×10^{-5}
Thyroid	0.07	3.8×10^{-5}	2.7×10^{-6}	1.4×10^{-6}	9.7×10^{-7}	4.2×10^{-6}	3.0×10^{-7}
Leukemia	0.67	8.3×10^{-4}	5.5×10^{-4}	6.3×10^{-4}	4.3×10^{-4}	6.3×10^{-4}	4.2×10^{-4}
Bone	0.45	1.7×10^{-6}	7.4×10^{-7}	1.3×10^{-6}	6.0×10^{-7}	1.0×10^{-6}	4.5×10^{-7}
Skin	0.002	2.4×10^{-4}	4.7×10^{-7}	2.3×10^{-4}	4.7×10^{-7}	2.3×10^{-4}	4.5×10^{-7}
Breast	0.29	2.2×10^{-3}	6.4×10^{-4}	1.3×10^{-3}	3.7×10^{-4}	7.2×10^{-4}	2.1×10^{-4}
Ovary	0.57	1.5×10^{-4}	8.4×10^{-5}	1.1×10^{-4}	6.1×10^{-5}	7.3×10^{-5}	4.2×10^{-5}
Other	0.49	9.0×10^{-4}	4.4×10^{-4}	6.6×10^{-4}	3.2×10^{-4}	4.5×10^{-4}	2.2×10^{-4}
Total			3.6×10^{-3}		2.8×10^{-3}		2.3×10^{-3}

Table VIII. Radiation detriment results for adult males

Category	Age	Dose	REID Risk	
			M	F
Nuclear Industry	46-year career	20mSv / year (920mSv)	$R \leq 4.6\%$ [4]	
RES-1	20s	$D \leq 70$ cGy	$R \leq 2.45\%$	$R \leq 2.52\%$
	30s		$R \leq 1.82\%$	$R \leq 1.96\%$
	40s		$R \leq 1.47\%$	$R \leq 1.61\%$
RES-2	20s	70 cGy $< D \leq 150$ cGy	$R \leq 5.25\%$	$R \leq 5.40\%$
	30s		$R \leq 3.9\%$	$R \leq 4.20\%$
	40s		$R \leq 3.15\%$	$R \leq 3.45\%$
RES-3	20s	150 cGy $< D$	$5.25\% < R$	$5.40\% < R$
	30s		$3.9\% < R$	$4.20\% < R$
	40s		$3.15\% < R$	$3.45\% < R$

As presented in Table VIII, from a long-term perspective, radiation exposure to military operations does not result in a significantly higher REID compared to the nuclear industry. However, from a short-term perspective, military personnel are at greater risk of acute radiation syndrome (ARS) due to potential exposure to high-intensity radiation, which is relevant to RES-2 and 3, as ARS typically manifests at radiation doses exceeding 1 cGy. At this dose level, the mortality rate remains below 5%, but the risk of acute health effects is still significant [5]. Additionally, military operations involve other immediate and severe hazards, including explosions and direct combat engagements, which present significantly greater risks to personnel than long-term radiation exposure.

Considering these additional risks, the industrial sector experiences fatalities due to occupational accidents, whereas military personnel face combat-related casualties. The occupational fatality rate in the industrial sector is approximately 0.000098% [6], while the military fatality rate, based on recent Russia-Ukraine war, is approximately 12% [7, 8].

This contrast highlights the fundamental differences in risk assessment approaches between the two sectors. The industrial sector prioritizes strict safety measures to mitigate occupational hazards, while the military sector evaluates risks primarily from a mission-critical perspective, where operational effectiveness often takes precedence over individual safety.

4. Conclusions

This study compared radiation exposure standards between occupational and military environments, highlighting key differences in risk assessment and dose limitations. While the nuclear industry adheres to strict regulatory frameworks designed to minimize exposure, military standards often allow for higher permissible doses due to operational necessities. In the nuclear industry, strict regulations ensure that long-term exposure remains within acceptable risk thresholds.

In contrast, military radiation exposure standards prioritize operational effectiveness, allowing for higher permissible doses in emergency conditions. The OEG provides a structured framework for managing radiation risks in battlefield scenarios while minimizing unnecessary exposure.

The calculated REIC and REID values for different age groups and genders demonstrate that younger individuals face a higher REID when exposed to radiation. This underscores the importance of age-specific exposure limits in radiation risk management.

Balancing radiation safety with operational demands are critical in both sectors, as each faces distinct challenges. In the nuclear industry, maintaining strict exposure limits requires continuous monitoring, regulatory compliance, and risk mitigation strategies to protect workers. Conversely, military operations often demand flexibility, where exposure limits may be adjusted based on mission urgency, requiring real-time risk assessment and adaptive protective measures to ensure both operational success and personnel safety. Future research should refine risk models and optimize protective measures to ensure personnel safety while maintaining mission effectiveness.

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