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Modelling and Analysis the Cancer Incidence and Mortality Risks for Occupationally Workers with TE-NORM

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Abstract

In many industrial fields, a significant number of workers are regularly faces elevated doses of natural background radiation. Uncontrolled handling of Technologically Enhanced Naturally Occurring Radioactive Materials (TE-NORM) can lead to environmental pollution and serious health hazards. These dangers can be mitigated by applying effective control measures, including identifying NORM presence, decontaminating equipment, adopting safe waste disposal practices, and prioritizing worker safety. This study is dedicated to assess the excess cancer risk—both relative and absolute—linked to occupational exposure to ionizing radiation across different industries, utilizing the BEIR VII risk model. The results indicate that all analyzed TE-NORM samples exceed recommended safety limits. In particular, petroleum scale and sludge samples show annual effective dose levels that go beyond occupational exposure thresholds, while other TE-NORM samples remain within permissible safety standards. The findings confirm that individuals handling TE-NORM, especially in oil-related industries, face an unavoidable risk of cancer, emphasizing the need to classify them as occupational radiation workers. This research highlights the importance of applying essential radiation protection principles through effective safety measures in industrial settings. Controlling exposure and conducting thorough dosimetry assessments are crucial aspects of a comprehensive health and safety program

Keywords: *BEIR VII risk model, TE-NORM waste, radiological hazards, risk analysis*

Introduction

TE-NORM (rock, soil, and minerals) that has increased its radioactive content due to industrial activities (Loan et al., 2021; Nabhani et al., 2016; Osmanlioglu, 2021; Wisnubroto, 2003).

TENORM can provide external and internal radiation exposure effects on workers and the surrounding industrial site. Workers or the local area receives external radiation because TENORM has contaminated offices. In contrast, internal radiation exposure is obtained through inhalation, food, and drink contaminated by TENORM. Suppose someone breathes air containing radioactive particles, drinks water, and eats food that already contains radioactivity or makes direct contact. In that case, they will be vulnerable to cancer onset or additional health problems. TENORM is generally found in mining areas, especially in Uranium mining (Haryoto et al., 2023). The BEIR VII report, released in 2006 by the National Academy of Sciences (NAS)' National Research Council, analyzed contemporary studies regarding health impact from low-dose, low-LET radiation exposure. This committee established models to estimate these risks.

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Risks of Radiation-Induced Cancers

Different models are employed to assess the likelihood of cancers caused by radiation. The excess relative risk (ERR) model is used for cancers where the increase in incidence correlates proportionally with the underlying baseline rates, regardless of population differences. Conversely, the excess absolute risk (EAR) model supposes radiation adds a fixed number of cases regardless of baseline rates. The BEIR VII Committee utilized both models to assess site-specific cancer risks (NAS, 2006).

The association between occupational ionizing radiation exposure and cancer has been studied since the 1940s when researchers discovered that radiologists had higher leukemia-related mortality rates than other medical professionals. Many industries handle unprocessed substances that possess naturally occurring radioactive materials (NORM), which undergo extraction, shipping, and refinement for various applications. These activities release radionuclides into the air and water, resulting in human exposure. Certain occupational groups, particularly nuclear sector employees, provide valuable data for evaluating the biological impacts of prolonged exposure to reduced levels and slow rates of ionizing radiation.

For both workers and the general public protection, it is essential to evaluate industrial processes and waste management practices involving NORM. TE-NORM are naturally occurring radioactive substances whose exposure risks have been amplified by human activities. In risk assessment, "risk" refers to the probability of a specific disease onset during a given timeframe, assuming the individual was initially disease-free. Similar to incidence rates, risk is time-dependent and can be mathematically expressed as:

Risk = Rate × Time.

Method

Total cancer risk figures were determined by aggregating the risk assessments for individual cancer types. However, the overall model framework and estimated parameters—accounting for factors such as exposure age and current age—were derived from data analyses across all solid cancer cases. Incidence analyses excluded thyroid cancer and non-melanoma skin cancers due to their unique dependence on age at exposure, which differs from other cancer types. Since these cancers have low fatality rates, mortality data analyses concentrated on the broader group of all solid cancers.

Table 1 presents parameter estimates for the ERR and EAR models. These estimates are derived from Life Span Study (LSS) incidence data (1958–1998), which covers solid cancers, except skin cancers (non-melanoma) and thyroid cases, as well as LSS mortality data (1950–2000) covering all solid carcinomas (2).

Table 1: ERR and EAR Model Parameters for Cancer Incidence and Mortality Assessment, Except for Skin Cancers (Thyroid and Non-Melanoma)

	ERR/Sv (95% CI) at Age 30 and Achieved Age 60				
ERR Models	Cases or Deaths Number	Males (β_M)	Females (β_F)	Ten-year incremental change in exposure age (0-30 year range) (95% CI), γ	Exponent of A, (95% CI) reached Age η
Incidence	12,667	0.30	0.55	-0.33	-1.2
Mortality	10,026	0.20	0.43	-0.52	-0.62
	EAR per 10^4 PY-Sv (95% CI)				
EAR Models		Males (β_M)	Females (β_F)		
Incidence	12,667	23	29	-0.45	2.9
Mortality	10,026	10	11	-0.32	3.2

NOTE: PY = person-years. Estimated parameters with 95% confidence intervals (CIs). The ERR or EAR is expressed in the following form (2):

ERR or EAR = β_s D exp (γe^*) $(a / 60)^{\eta}$,

The parameter D represents the radiation dose, measured in Sieverts (Sv), while e denotes the individual's age (in years) at exposure. The adjusted age variable, e*, is calculated as (e−30)/10(e - 30) / 10 for individuals younger than 30 and is set to zero for those aged 30 or older. Additionally, a represents the reached age (in years). γ indicates the rise in risk per decade for individuals exposed between birth and 30 years of age, whereas η denotes the reached age exponent.

Excess Relative Risk (ERR) represents the proportional rise in disease occurrence between exposed and unexposed populations. In contrast, Excess Absolute Risk (EAR) is determined by subtracting the disease rate of an unexposed group from that in an exposed group, standardized as excess deaths per 10^4 person-years per Sievert (PY-Sv).

To estimate leukemia risk, models were derived from the Life Span Study (LSS) data on leukemia mortality spanning 1950 to 2000 (7). The leukemia mortality data (non-type-specific) employed in this study is considered elevated. Utilizing a linear-quadratic model, the BEIR VII Committee evaluated leukemia risk while accounting for sex, exposure age, and post-exposure duration.

The BEIR VII leukemia risk model is given as:

EAR (D, s, e, t) or ERR(D, s, e, t) = $\beta_s D (1 + \theta D) \exp [\gamma e^* + \phi e^* \log (t / 25) + \delta \log (t / 25)]$ (2)

In this equation:

- D represents the dose received by the bone marrow (Sv),
- s denotes sex,
- e* follows the same definition as earlier ((e – 30) /10 for e < 30 and 0 for e ≥ 30),
- γ, δ, and ϕ are model-fitting parameters.

Table 2 presents the estimated values of these parameters. The θ parameter represents the degree of curvature in the model and remains independent of sex, exposure age, or post-exposure duration. The coefficients βM and βF correspond to the ERR/Sv or EAR values, which indicate excess deaths per 10^4 PY-Sv for individuals exposed at age ≥30, with risk assessed 25 years post-exposure.

Table 2: Fitting parameters for the ERR and EAR models used to estimate leukemia incidence and mortality

Parameter	EAR Model	ERR Model
β_F	0.93 deaths per 10^4 PY-Sv	1.2 per Sv
β_M	1.62 deaths per 10^4 PY-Sv	1.1 per Sv
γ	0.29 per decade	-0.40 per decade
δ	0.0	-0.48
ϕ	0.56	0.42
θ	0.88 Sv^{-1}	0.87 per Sv

NOTE: Parameters estimates include 95% confidence intervals derived from likelihood ratio profile.

User-friendly and efficient computational codes were developed, tested, and implemented to solve the ERR and EAR models. These models were utilized to estimate the occurrence of solid cancers (except non-melanoma and thyroid skin cancers), mortality from these cancers, as well as the ERR and EAR for leukemia.

The annual effective dose was calculated using various TE-NORM samples collected from multiple industrial sectors, including petroleum, phosphate fertilizers, consumer products, and ceramics. Spectral analysis of the samples was conducted with a p-type HPGe closed-end coaxial gamma spectrometer. The detector was vertically configured within a Pop Top-cryostat system and liquid nitrogen cooling.

The activity concentrations of different radionuclides were determined, along with the absorbed dosage. Finally, the annual effective dose was computed using Equation (8).

$$E_{eff} = D \times 8760 \times 0.7 \times \frac{10^3 mSv}{10^9 nGy} \times 0.2$$

in this equation, E_{eff} denotes the annual effective dose (in mSv), D denotes the absorbed dose rate in (nGy/h)

Incidence Rates and Excess Risks

The incidence rate is a fundamental component in the stochastic disease modeling. As a result, the methods and models used to analyze the exposure-disease relationship are typically expressed using incidence rates.

Within this framework, individuals are categorized using factors like age, sex, calendar time, and other relevant variables associated with disease development. Incidence rates are then calculated for each specific group.

In a simplified case with only two exposure groups—unexposed and exposed —let λU(t) and λE(t) represent the disease incidence for the both groups, respectively. If disease incidence is independent of exposure, then λE(t) = λU(t). However, any deviation from this equality suggests a potential relationship between exposure and disease risk.

A commonly used metric to quantify differences in incidence rates is the discrepancy measure, which helps assess the degree of correlation between exposure and disease incidence.

EAR (t) = λ_E (t) – λ_U (t), (4)

Traditionally, this is referred to as EAR, although technically, it represents a rate difference [BEIR VII, 2006].

This equation can be reformulated to express:

λ_E (t) = λ_U (t) + EAR (t), (5)

This demonstrates that EAR(t) represents the elevated rate of disease occurrence due to exposure. For instance, if EAR remains unchanged, such that EAR(t) = b, then exposure results in a uniform increase of b in incidence rates across all time periods. Notably, when b = 0, it indicates no correlation between exposure and disease incidence.

Another commonly used metric for comparing risks is the Relative Risk (RR), calculated as:

RR (t) = λ_E (t) / λ_U (t) (6)

This equation can be reformulated to express:

λ_E (t) = RR (t) λ_U (t), (7)

The RR function quantifies how exposure amplifies incidence rates multiplicatively. In cases where RR shows no temporal variation, it simplifies to RR(t) = r, suggesting exposure consistently modifies disease rates by a constant factor r.

- r > 1 indicates that exposure elevates disease risk.
- r < 1 implies a protective effect of exposure.
- If r = 1, it signifies no exposure-disease relationship (BEIR VII, 2006).

The ERR function, ERR(t), is defined as:

ERR (t) = RR (t) – 1. (8)

The incidence rates for exposed (λE) and unexposed (λU) groups are connected through the ERR model

λ_E (t) = λ_U (t) 1 + ERR (t)}. (9)

The Probability of Causation (PC) represents the chance that a certain cancer case in a definite tissue was induced by prior exposure to a known carcinogen (e.g., radiation). To compute PC, researchers model the ERR based on radiation dose and other relevant factors (BEIR VII, 2006), systematically analyzing how exposure influences cancer risk.

PC = Exposure-related risk/ Baseline + Exposure-related risk

PC = ERR / (1+ERR) (10)

Estimating Cancer Risk

- A key objective of the BEIR VII (2006) committee was to construct risk models aimed at evaluating how exposure to low doses of low-LET ionizing radiation relates to potential health impacts. They determined that the Linear No-Threshold (LNT) model most accurately characterizes the dose-response relationship for radiation-induced solid malignancies.
- To assess lifetime cancer risk at varying radiation dose levels, the committee introduced models that estimate both cancer occurrence and mortality, accounting for factors like sex, exposure age, dose rate, and additional risk modifiers. These risk estimates cover all solid cancers, leukemia, and certain cancer types.
- Several factors influence cancer risk, including:
- Cancer type,
- Radiation dose and quality,
- Dose rate,
- Individual's age and sex,
- Exposure to other carcinogens (e.g., tobacco), and additional contributing elements

Exposed Individual Characteristics & Risk Estimation Models

Also, this section introduces validated computational algorithms designed to numerically to solve the risk estimation models.

The risk estimation models primarily depend on data from the LSS cohort, which includes survivors of the Hiroshima and Nagasaki atomic bombings. The LSS cohort is particularly valuable for assessing radiation-related cancer risks due to several key advantages:

- Large sample size,
- Inclusion of both genders and all age groups,
- Availability of individual dose estimates across a wide range,
- High-quality data on mortality and cancer incidence,
- Whole-body radiation exposure, enabling risk assessments for multiple cancer types.

The LSS data allows for the evaluation of cancer risks for individual organs and comparisons across different organs. Research suggests that relative risk is highest within one to five years post-exposure. However, the BEIR VII committee postulated that excess absolute risk between two and five years post-exposure would be comparable to the risk identified five years following exposure.

Despite these insights, uncertainty remains regarding the precise risk magnitude in the early years after radiation exposure, highlighting the need for further research and enhanced risk modeling.

Models for All Solid Cancers

The comprehensive risk estimates for solid cancers were derived by aggregating the calculated risks for individual cancer types. However, the overall model structure and the parameters used to evaluate the impact of exposure age and achieved age depend on comprehensive analysis of data covering all solid cancers. These analyses benefit from a larger dataset of cancer cases and deaths, enhancing the statistical reliability of the estimates.

The models were established using data from LSS incidence and mortality studies. The incidence data analyses focused on all solid cancers, except thyroid and non-melanoma skin cancers, as these cancers exhibit distinct age-related dependencies that differ from other cancer types. Since these cancers are rarely fatal, mortality analyses were conducted on all solid cancers, excluding these two types.

The models employed to assess solid cancer risks—both ERR and EAR—consider exposure age as a modifying factor only for individuals exposed before age 30. In case of exposure at 30 years or older, the risk is assumed to remain constant. As per the BEIR VII (2006) model, the risk estimation formula is:

$$\text{ERR}\,(e, a) \text{ or EAR}\,(e, a) = \exp\,(\gamma\, e^*)\, a^{\eta} \qquad (11)$$

where:

- **e** = Exposure age (in years),
- **e*** = (e – 30) when **e < 30**, otherwise **0**,
- **a** = Achieved age (in years),
- **γ** = Ten-year incremental change in exposure age under 30 years,
- **η** = Exponent of achieved age.

This model (Equation 11) was found to be the best fit for cancer occurrence and mortality data, except non-melanoma and thyroid skin cancers.
Refined BEIR VII Model for ERR and EAR

The preferred BEIR VII model for ERR or EAR is expressed as:

$$\text{ERR or EAR} = \beta_s\, D \exp\,(\gamma e^*)\,(a / 60)^{\eta}, \qquad (12)$$

where:

- D = Radiation dose (in Sieverts),
- e = Exposure age (years),
- e* = (e – 30)/10 when e < 30, otherwise 0,
- a = Achieved age (years),
- βs = Fitting parameter dependent on sex, with βM for males and βF for females.

Table (3) presents the estimated values for the ERR and EAR models using LSS incidence data (1958–1998) and LSS mortality data (1950–2000) for all solid cancers, except non-melanoma and thyroid skin cancers (BEIR VII, 2006).

Table 3: ERR and EAR models used to estimate incidence of all solid cancers, except thyroid and non-melanoma skin cancers and mortality associated with solid cancers

	ERR/Sv (95% CI) at Age 30and achieved Age 60				
ERR Models	**Cases or Deaths number**	**Males(β_M)**	**Females(β_F)**	**Ten-year incremental change in exposure age (0-30 year range) [a] with (95% CI), γ**	**Exponentof A, (95% CI) achievedAge, η**
Incidence	12.667	0.30	0.55	-0.33	-1.2
Mortality	10.026	0.20	0.43	-0.52	-0.62
	EAR per 10^4 PY-Sv (95% CI)				
EAR Models		**Males (β_M)**	**Females (β_F)**		
Incidence	12.667	23	29	-0.45	2.9
Mortality	10.26	10	11	-0.32	3.2

NOTE: Estimates are presented with 95% CIs. PY = person-years.

For every ten-year rise in exposure age, the modification in ERR/Sv or EAR/10^4 PY-Sv equals 1 – exp (γ).

Result and discussion

Development of Risk Assessment Computer Codes

User-friendly computer programs were designed, tested, and developed to evaluate radiation exposure-related cancer risks, specifically all solid cancers (except non-melanoma and thyroid skin cancers) across different sexes and ages.

Two separate codes were implemented:

1. EAR Model – Computes incidence and mortality rates for solid cancers.
2. The ERR model estimates incidence and mortality rates according to relative risk. Additionally, these codes calculate the PC for cancer incidence and mortality.
3. Tables 4-6 present the calculated radiation risks for individuals receiving 0.1 Sv exposures at different ages, evaluated after a 5-year latency period, with corresponding graphical illustrations in Figures 1-3.

Table (4) presents the EAR for cancer incidence and mortality per 10^4 PY-Sv for all solid cancers, except non-melanoma and thyroid skin cancers, in individuals under 0.1 Sv exposure at varied ages, five years' post-exposure.

Table 4: EAR of cancer incidence and mortality for all solid cancers, except non-melanoma and thyroid skin cancers, in individuals exposed to 0.1 Sv at varied ages, assessed five years' post-exposure

Age at Exposure (years)	(EAR) Incidence ($\times10^{-2}$)		(EAR) Mortality ($\times10^{-2}$)	
	Male	Female	Male	Female
0	0.698	8.890	0.0562	0.0695
5	4.20	5.33	0.541	0.620
10	9.90	12.2	1.50	2.11
15	17.4	22.6	3.90	4.70
20	26.8	34.6	8.20	7.89
30	46.8	62.0	17.6	19.8
40	93.8	122	40.4	47.6
50	174	220	82.1	96.1
60	271	350	147	173
70	411	523	240	284

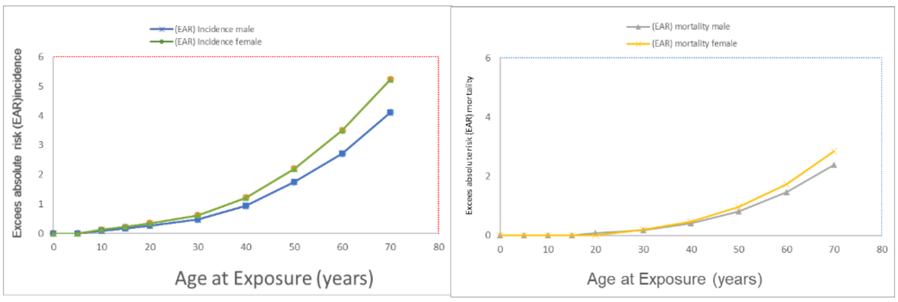

Fig. 1: EAR of cancer incidence and mortality per 10^4 PY-Sv for all solid cancers, except non-melanoma and thyroid skin cancers

Table 5: ERR of cancer incidence and mortality for all solid cancers, except non-melanoma and thyroid skin cancers, in individuals exposed to 0.1 Sv at varied ages, assessed five years' post-exposure.

Age at Exposure (years)	(ERR) Incidence ($\times 10^{-3}$)		(ERR) Mortality ($\times 10^{-3}$)	
	Male	Female	Male	Female
0	2593	4560	625	1331
5	867	1472	310	621
10	420	724	187	370
15	239	420	109	230
20	161	271	73.0	151
30	70.3	132	32.9	66.9
40	50.1	85.4	28.0	57.1
50	36.9	65.1	21.0	50.1
60	31.0	51.2	22.0	45.2
70	24.3	42.4	20.3	41.2

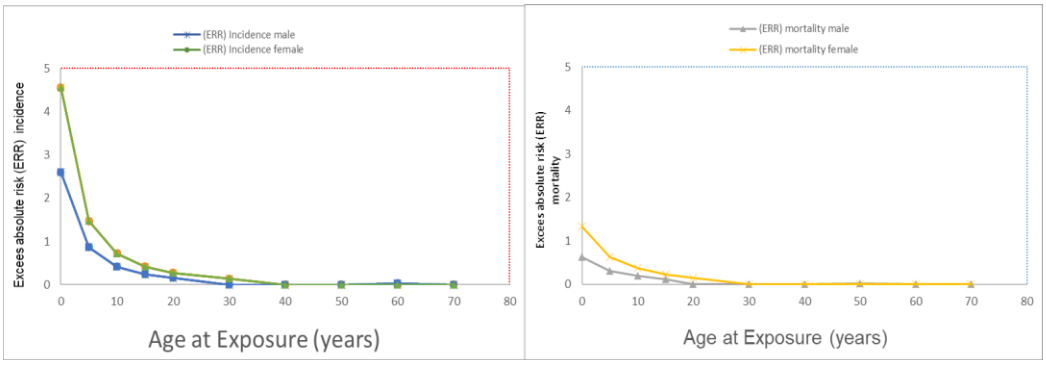

Fig. 2: ERR of cancer incidence and mortality for solid cancers, except non-melanoma and thyroid skin cancers.

Table 6: Probability of Causation (PC) for cancer incidence and mortality in individuals exposed to 0.1 Sv at varied ages, assessed five years' post-exposure, for solid cancers except non-melanoma and thyroid skin cancers

Age at Exposure (years)	(PC) Incidence ($\times 10^{-3}$)		(PC) Mortality ($\times 10^{-3}$)	
	Male	Female	Male	Female
0	730	820	401	621
5	501	613	241	391
10	301	422	163	276
15	205	324	85	194
20	123	210	68.1	134
30	66.5	121	32.1	62.3
40	51.0	79.1	26.8	54.3
50	36.4	61.4	24.9	46.8
60	27.8	49.2	23.2	43.5
70	24.2	41.0	23.0	39.1

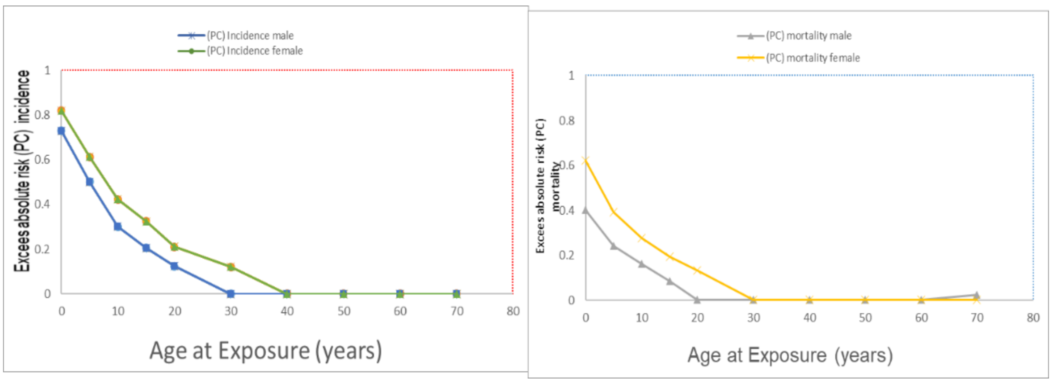

Fig. 3: PC for cancer incidence and mortality in all solid cancers, except non-melanoma and thyroid skin cancers.

Analysis of Cancer Risk Estimates

Table 4 reveals an age-dependent increase in excess absolute risk (per 10^4 PY-Sv) for both cancer incidence and mortality among individuals receiving 0.1 Sv exposures, with consistently elevated risks observed in female populations compared to males. These findings exclude non-melanoma skin cancers and thyroid malignancies.

Tables (5) and (6) reveal that the ERR for both incidence and mortality under similar exposure conditions decreases with increasing age for both genders. Nevertheless, ERR and the PC remain lower in males than females.

The computational models developed in this study facilitate flexible risk calculations for exposure age, reached age, and radiation dose. To illustrate their versatility, the relationship between attained age and risk has been analyzed.

For instance, the EAR for incidence and mortality (per 10^4 person-years per sievert) for individuals exposed to 0.1 Sv at ages 20 and 30+ is presented in Tables (7) and (8) and visualized in Figures (4) and (5). Similarly, the ERR for incidence and mortality for individuals exposed to 1 Sv at ages 20 and 30+ is provided in Tables (9) and (10) and depicted in Figures (6) and (7).

Comparison of ERR and EAR Models

Both the ERR and EAR models share a similar general structure, but their parameter values and interpretations differ. Based on the tables and figures:

- ERR decreases with attained age, whereas EAR increases significantly with reached age.
- For individuals exposed before the age of 30, both ERR and EAR tend to decrease as the age at exposure increases.
- ERR and EAR were higher in females compared to males under identical exposure conditions.

Table 7: EAR for cancer incidence and mortality per 10^4 person-years per sievert for solid cancers, except non-melanoma and thyroid skin cancers, in individuals exposed to 0.1 Sv at age 20.

Reached age (years)	(EAR) Incidence ($\times10^{-2}$)		(EAR) Mortality ($\times10^{-2}$)	
	Male	Female	Male	Female
30	51.2	61.3	11.4	17.1
35	71.3	94.2	22.4	29.2
40	105.6	136.5	35.8	46.1
45	149.4	189.1	57.7	69.4
50	199.8	252.1	83.6	98.9
55	262.1	331.4	118.1	139.2
60	332.4	422.3	161.2	192.3
65	415.3	528.1	212.4	250.1
70	510.5	650.3	272.3	323.4
75	623.4	790.3	348.1	412.4

Table 8: EAR of cancer incidence and mortality per 10^4 PY-Sv for all solid cancers, except non-melanoma and thyroid skin cancers, in individuals aged 30 and above exposed to 0.1 Sv.

Reached age(years)	(EAR) Incidence ($\times10^{-2}$)		(EAR) Mortality ($\times10^{-2}$)	
	Male	Female	Male	Female
40	71.3	92.3	27.0	32.4
45	98.1	126.3	43.4	48.2
50	133.1	169.2	57.8	69.4
55	174.2	221.0	80.1	96.3
60	219.0	278.0	109.8	129.9
65	272.5	351.3	146.2	171.9
70	339.2	430.2	189.3	223.0
75	411.4	524.1	243.0	284.1

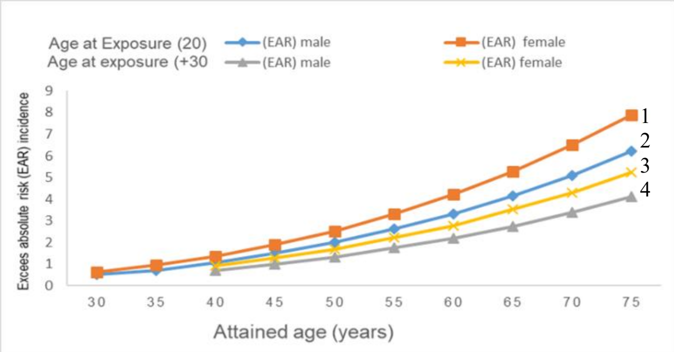

Fig. 4: EAR of cancer incidence per 10^4 PY-Sv for solid cancers, except non-melanoma and thyroid skin cancers. The curves represent risk estimates for both sexes at a 0.1 Sv exposure, with lines (1 , 2) indicating exposure at age 20 and lines (3 ,4) representing exposure at age 30 or older.

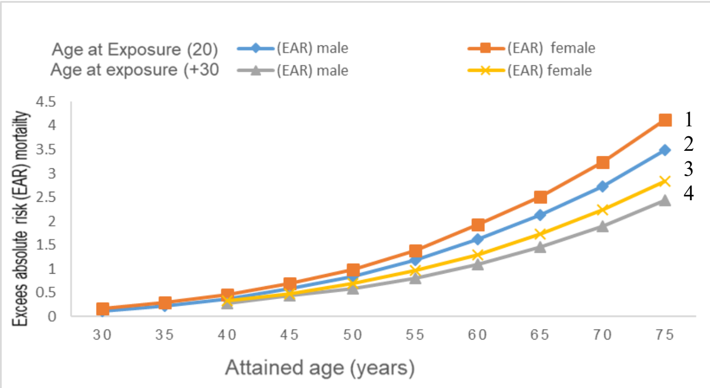

Fig. 5: EAR of cancer mortality per 10^4 PY-Sv for solid cancers, except non-melanoma and thyroid skin cancers. The curves represent risk estimates for both sexes at a 0.1 Sv exposure, with lines (1, 2) indicating exposure at age 20 and lines (3,4) representing exposure at age ≥30.

Table 9: ERR of cancer incidence and mortality for solid cancers, except non-melanoma and thyroid skin cancers, in individuals exposed to 1 Sv at age 20.

Reached age (years)	(ERR) Incidence ($\times10^{-2}$)		(ERR) Mortality ($\times10^{-2}$)	
	Male	Female	Male	Female
30	118.1	202.9	65.2	131.0
35	95.4	164.2	58.2	117.9
40	79.1	136.2	53.4	108.1
45	67.1	115.4	49.0	99.9
50	58.1	99.4	46.3	93.3
55	51.0	87.2	43.4	88.1
60	45.2	77.1	43.0	83.4
65	40.1	69.1	39.1	78.0
70	36.2	61.9	37.3	73.9
75	33.1	57.1	35.1	71.7

Table 10: ERR of cancer incidence and mortality for solid cancers, except non-melanoma and thyroid skin cancers, in individuals aged 30 and above exposed to 1 Sv.

Reached age (years)	(ERR) Incidence ($\times10^{-2}$)		(ERR) Mortality ($\times10^{-2}$)	
	Male	Female	Male	Female
40	59.2	109.0	30.3	62.4
45	52.3	85.4	28.3	57.1
50	43.5	74.3	26.2	51.3
55	36.5	65.3	26.2	49.9
60	32.9	56.8	22.7	46.7
65	32.1	51.4	22.8	45.4
70	27.1	46.3	21.5	43.5
75	25.2	42.6	19.2	41.6

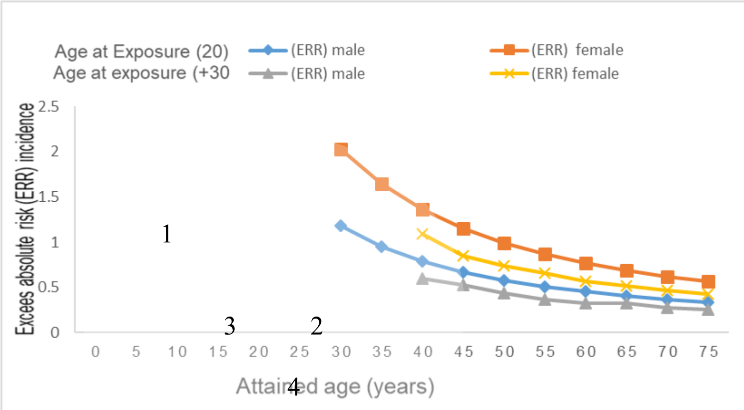

Fig. 6: ERR of cancer incidence for all solid cancers, except non-melanoma and thyroid skin cancers. The curves represent risk estimates for both sexes at a 1 Sv exposure, with lines (1 ,3) indicating exposure at age 20 and lines (2, 4) representing exposure at age ≥30.

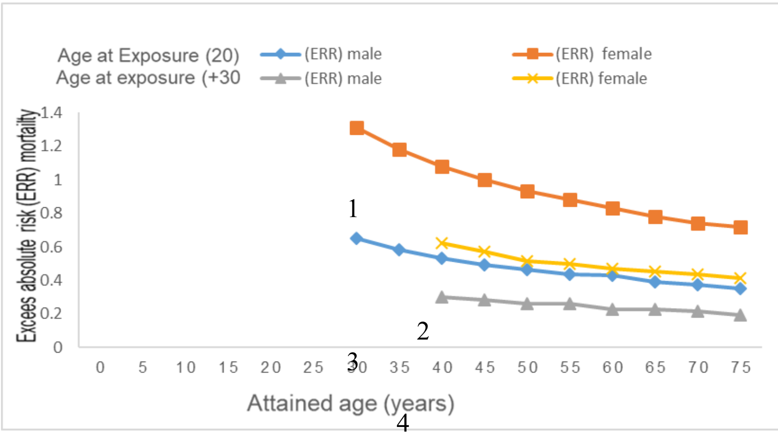

Fig. 7: ERR of cancer mortality for all solid cancers, except non-melanoma and thyroid skin cancers. The curves represent risk estimates for both sexes at a 1 Sv exposure, with lines (1 ,3) indicating exposure at age 20 and lines (2 ,4) representing exposure at age 30 or older.

Application of Cancer Risk Analysis

This section examines cancer risk among occupational workers across various industrial sectors. The data provides risk estimates for workers aged 30 and above who are exposed to radiation from different TE-NORM samples. The risk calculations were performed using the computer models developed and validated in this study.

Risk Assessment of All Solid Cancers for Workers in Different Industrial Sectors

Table (11) presents estimates of ERR and EAR for both cancer incidence and mortality in male workers, except non-melanoma and thyroid skin cancers. These risk estimates were generated using the specialized software developed in this study.

Key Observations from Table (11)

- Petroleum TE-NORM samples pose a higher cancer risk for workers handling scale compared to sludge.
- Contaminated sand presents a risk, but it is significantly lower than that associated with scale and sludge.
- Phosphate fertilizers exhibit minimal risk due to their low radiation dose.
- Consumer products manufactured in China show an overall low risk; however, this risk remains higher than that associated with fertilizers and ceramics.
- Ceramic materials pose a low risk to workers.
- Zircon presents a relatively high risk, attributed to its elevated radiation dose.

Trends in Risk Estimates

- **ERR (Excess Relative Risk)** decreases with attained age, while **EAR (Excess Absolute Risk)** increases with attained age.
- Cancer risk significantly rises with increasing levels of radiation exposure.

This study underscores the importance of effective radiation protection measures to safeguard workers from occupational radiation hazards in industries involving TE-NORM materials.

Table 11: ERR and EAR for cancer incidence and mortality in male workers aged 30, engaged in various industrial activities under study, except non-melanoma and thyroid skin cancers.

			Incidence				Mortality			
			ERR/Sv		EAR/10^4 PY-Sv		ERR/Sv		EAR/10^4 PY-Sv	
TE- NORM From	Estimated Dose (mSv/y)		Reached age 50	Reached age 60	Reached age 50	Reached age 60	Reached age 50	Reached age 60	Reached age 50	Reached age 60
Petroleum scale	Min.	84.2	3.59×10^{-2}	0.029	1.08	1.79	2.3×10^{-2}	0.030	0.48	0.93
	Max.	243.5	0.09	0.07	3.1	5.21	6.4×10^{-2}	0.059	1.40	2.68
	Avg.	161.1	0.06	0.04	2.19	3.7	4.1×10^{-2}	0.038	0.96	1.80
Petroleum sludge	Min.	13	5.1×10^{-3}	0.002	0.18	0.28	3.1×10^{-3}	0.003	0.09	0.13
	Max.	66.1	3.0×10^{-2}	0.023	0.87	1.39	1.8×10^{-2}	0.02	0.39	0.73
	Avg.	29.01	1.2×10^{-2}	0.02	0.39	0.65	7.6×10^{-3}	0.008	0.18	0.31
Petroleum sand	Min.	0.33	1.3×10^{-4}	1.1×10^{-4}	4.4×10^{-3}	7.3×10^{-3}	8.9×10^{-5}	7.9×10^{-5}	2.1×10^{-3}	3.8×10^{-3}
	Max.	6.36	2.8×10^{-3}	0.003	0.85	0.13	1.6×10^{-3}	0.002	0.38	0.06
	Avg.	1.59	6.8×10^{-4}	5.1×10^{-4}	2.2×10^{-2}	0.04	4.2×10^{-4}	3.5×10^{-4}	9.1×10^{-3}	0.03
Phosphate fertilizers	Min.	0.036	1.5×10^{-5}	1.3×10^{-5}	5.1×10^{-4}	8.5×10^{-4}	1×10^{-5}	8.9×10^{-6}	2.3×10^{-4}	4.2×10^{-4}
	Max.	1.852	8.1×10^{-4}	6.1×10^{-4}	2.3×10^{-2}	0.03	4.9×10^{-4}	4.2×10^{-4}	1.2×10^{-2}	0.03
	Avg.	0.432	1.9×10^{-4}	1.3×10^{-4}	5.7×10^{-3}	9.3×10^{-3}	1.2×10^{-4}	10×10^{-5}	2.6×10^{-3}	4.8×10^{-3}
Consumer product	Min.	0.76	3.1×10^{-4}	2.3×10^{-4}	10.1×10^{-3}	1.7×10^{-2}	2.1×10^{-4}	1.8×10^{-4}	4.5×10^{-3}	8.3×10^{-3}
	Max.	2.37	0.9×10^{-3}	7.9×10^{-4}	3.2×10^{-2}	5.3×10^{-2}	6.2×10^{-4}	5.3×10^{-4}	1.5×10^{-2}	2.7×10^{-2}
	Avg.	1.90	8.2×10^{-4}	6.3×10^{-4}	2.6×10^{-2}	4.2×10^{-2}	5.1×10^{-4}	4.4×10^{-4}	1.2×10^{-2}	2.2×10^{-2}
Ceramic	Min.	0.51	2.3×10^{-4}	1.8×10^{-4}	6.8×10^{-3}	0.02	1.4×10^{-4}	1.3×10^{-4}	3×10^{-3}	0.007
	Max.	0.87	3.8×10^{-4}	2.9×10^{-4}	1.2×10^{-2}	0.03	2.3×10^{-4}	2.1×10^{-4}	5.4×10^{-3}	0.010
	Avg.	0.62	2.7×10^{-4}	2.1×10^{-4}	8.2×10^{-3}	0.02	1.7×10^{-4}	1.5×10^{-4}	3.7×10^{-3}	0.008
Zircon	14.5		6.3×10^{-3}	4.9×10^{-3}	0.2	0.33	3.9×10^{-3}	3.4×10^{-3}	8.5×10^{-2}	0.17

Conclusion

Impact of TENORM Radiation Exposure on Workers' Health

TENORM radiation exposure can have adverse effects on workers' health (Ali et al., 2020; Gupta et al., 2014). A worker positioned near a radiation field receives a radiation dose proportional to their duration of exposure. As the time spent in a radiation area increases, so does the radiation dose absorbed by the worker (Malaka, 2019).

The main goal of assessing cancer risk among workers across varied industries is to evaluate the effectiveness of existing radiation protection measures. This study underscores the importance of mitigating occupational risks, particularly by considering the impact of low-dose-rate radiation exposure.

Adhering to workplace safety guidelines and utilizing personal protective equipment (PPE) can help reduce the risks associated with TENORM radiation exposure. Essential protective gear includes lab coats, gloves, boots, and shoe covers. Additionally, workers should wear respiratory protective equipment such as filter-type respirators and masks (Malaka, 2019).

Key Findings & Recommendations

1. **Occupational Cancer Risk:** Workers handling TE-NORM materials face an inherent cancer risk. To minimize exposure, precautionary measures, strict safety regulations, and the use of protective equipment must be enforced.
2. **High-Risk Industry:** Oil field workers experience the highest radiation exposure, making them the most vulnerable. They should be officially recognized as occupational radiation workers.
3. **Radiation Protection & Health Monitoring:** Compliance with radiation protection protocols is crucial. Regular medical checkups are necessary to detect early health effects.
4. **Expert Oversight:** Qualified radiation protection specialists should oversee TE-NORM operations to ensure worker and environmental safety during oil production, separation, and maintenance.
5. **Regulatory Enforcement:** Strict regulations must be applied to workers responsible for cleaning contaminated equipment, as this task poses significant radiation exposure risks.

By implementing these recommendations, radiation exposure risks can be minimized, ultimately safeguarding workers' health and safety in TE-NORM-related industries.

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