**HEALTH RISK ASSESSMENT FOR RADIUM DISCHARGED
IN PRODUCED WATERS**

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INTRODUCTION

Produced water generated during the production of oil and gas can contain enhanced levels of radium. This naturally occurring radioactive material (NORM) is discharged into freshwater streams, estuarine, coastal and outer continental shelf waters. Large volumes of produced waters are discharged to coastal waters along the Gulf Coast of Louisiana. The Gulf of Mexico is an important producer of fish and shellfish, and there is concern that radium discharged to coastal Louisiana could contaminate fish and shellfish used by people for food, and present a significant increase in cancer risk.

This paper describes a screening-level assessment of the potential cancer risks posed by radium discharged to coastal Louisiana in oil-field produced waters. This screening analysis was performed to determine if a more comprehensive and realistic assessment is necessary, and because of the conservative assumptions embedded in the analysis overestimates the risk associated with the discharge of radium in produced waters.

RADIUM IN COASTAL LOUISIANA

Two isotopes of radium (Ra-226 and Ra-228) are the radionuclides of most concern in produced water in terms of potential human health effects. Radium isotopes probably make up the bulk of nuclide activity in produced water (Snively, 1989). Radium is important because of its high solubility in produced water and tendency to bioaccumulate in food organisms. Ra-226 and Ra-228 arise during the radioactive decay of their naturally occurring parent radionuclides. The isotopes of radium give rise to a series of radioactive daughters that lead to a stable isotope of lead. Radium-226, created from thorium-230, is a member of the uranium-238 decay series. Ra-226 has a half-life of 1602 years and decays to radon-222 through the emission of an alpha particle. Ra-228 is part of the thorium decay series, and its parent radionuclide is thorium-232. Ra-228 decays to Ac-228, and its primary emission is a beta particle.

Ra-226 and Ra-228 are naturally occurring radionuclides, and are present in the earth's crust, in freshwater rivers and lakes, and in coastal waters, oceans and sediments. Ra-226 concentrations in coastal waters have been reported to be between 0.01 and 0.59 pCi/l (Cherry and Shannon, 1974). A study of three produced water outfalls and six background stations in coastal Louisiana reported a range of background concentrations of 0.2 to 0.7 pCi/l for Ra-226 and 0 to 10.3 pCi/l for Ra-228 (CSA, 1991).

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The range of radium concentrations in produced waters discharged to coastal Louisiana was estimated from a data base compiled by the State of Louisiana. Ra-226 concentrations varied from 0 to 930 pCi/l, with an average concentration of 159.2 pCi/l. Ra-228 concentrations varied from 0 to 928 pCi/l, with an average of 164.5 pCi/l.

Radium in produced water undergoes rapid mixing and dilution when discharged to surface water. A study of three low energy, coastal produced water outfalls in Louisiana (CSA, 1991) demonstrated dilution factors of 148 to 1526 within 50 feet of the outfalls. These stations were considered worst case examples in terms of environmental impact because they are located in estuarine, low energy canal environments.

BIOACCUMULATION OF RADIUM BY FISH AND SHELLFISH

Radium is known to be accumulated by freshwater and marine organisms. Radium is a chemical analogue of calcium and tends to accumulate in bone, shell and exoskeleton. To describe the risk associated with the ingestion of radium in fish and shellfish harvested in coastal Louisiana, the extent of radium uptake by organisms used for food must be estimated.

Concentration factors are commonly used in risk assessment studies to estimate the levels of radionuclides in aquatic organisms. The concentration factor (CF) is a function of the concentration in the water or sediment (C) and the equilibrium concentration (on a wet weight basis) in the organism (Q).

$$\text{Seafood Conc. (Q)} = \text{Water Conc. (C)} \times \text{Concentration Factor (CF)} \quad (1)$$

This method assumes there is a linear relationship between C and Q and that the concentration factor is independent of the concentration in the environment. In reality, however, concentration factors are affected by many variables, including the species of animal and the concentration of radium in water.

The concentration factors commonly used in dose assessment studies (IAEA, 1982, 1985) are appropriate for screening-level assessments, but may overestimate the concentrations in edible portions of marine organisms. There are few studies available which describe concentration factors for radium in the edible portions of marine animals, but concentration factors of 100 appear to be conservative estimates for the edible portions of marine fish and shellfish (Table 1). A more recent recommendation in IAEA (1985) suggested larger concentration factors for radium in marine fish and molluscs. Table 1 summarizes the International Atomic Energy Agency (IAEA) recommended values, and values from the literature summarizing the concentration factors found in marine organisms used for food. The assessment described here used the values of 100 for fish, molluscs and crustaceans recommended in IAEA (1982).

HUMAN HEALTH EFFECTS

The health effects of radium can be attributed to the radioactive emissions of the isotopes and their daughters. The alpha, beta and gamma radiation released by the decay of radium and its daughters cause ionization of cellular components followed by the mutation or death of affected cells.

Most of the information concerning the health effects of radium come from studies of two groups of people: radium dial painters who ingested radium paint and patients who were injected with radium-224 for treatment of spinal arthritis and tuberculosis of the bone (NAS, 1988). Health effects associated with the ingestion of Ra-226

Table 1. Recommended concentration factors and reported values.

		Literature	IAEA (1982)	IAEA (1985)
Fish	flesh	21 - 130 ¹	100	500
	whole	2 - 100 ³		
Molluscs	soft parts	44 - 170 ^{1,2}	100	1000
	soft parts	2 - 240 ³		
Crustaceans	soft parts	35 - 360 ¹	100	100
	whole	4 - 170 ³		

¹ Iyengar et al., 1980

² Iyengar, 1984

³ Calculated from data in CSA (1991).

include bone sarcoma and cancer of the paranasal sinuses and mastoid air cells (NAS, 1988).

Current practice in radiation protection and risk assessment is to assume there is some cancer risk associated with even very low doses of radiation. Risk factors are derived from epidemiological data and extrapolated down to low doses to describe the cancer risk associated with small exposures. Using a model called RADRISK, and assuming a person drinks 2 liters of water each day, the United States Environmental Protection Agency (USEPA) has estimated the risk factor associated with the ingestion of Ra-226 in drinking water to be 4.4×10^{-6} per pCi/l lifetime, and the risk factor for Ra-228 to be 3.8×10^{-6} per pCi/l lifetime (Federal Register, 1991, USEPA, 1991). These values are equivalent to 2.2×10^{-6} per pCi/day lifetime and 1.9×10^{-6} per pCi/day lifetime.

The RADRISK model predicts the dose of ionizing radiation delivered to radiosensitive organs by radium and calculates cancer risk based on a synthesis of human epidemiologic data (USEPA, 1991). The RADRISK model results were adjusted for the overprediction of leukemias and lack of prediction of head carcinomas (USEPA, 1991). There is a large amount of uncertainty associated with these estimates. The analysis performed by the USEPA assumes a linear dose-response relationship for bone sarcoma, although the best fit for bone sarcoma in the radium dial painters is quadratic (USEPA, 1991). If the true relationship is quadratic, the USEPA risk factors will be overestimates. There may also exist a practical threshold for bone sarcoma (USEPA, 1991). Additional uncertainties and assumptions in the USEPA analysis are described in USEPA (1991). The assessment reported here used the current USEPA risk factors for radium.

RISK ASSESSMENT FOR RADIUM IN PRODUCED WATER

A health risk assessment for an environmental pollutant describes the discharge of the contaminant, its transport and fate in the environment and the associated human exposure. Human-health risks are then calculated based on data and models that relate exposures to risk (Till and Meyer, 1983). Two measures are commonly used to describe the probability that harm will result from exposure to a risk agent (Cohrssen and Covello, 1989): 1) Individual lifetime risk -- the estimated increase in probability that an individual will experience a specific adverse health effect as a result of exposure to a risk agent over a lifetime; and 2) Population risk -- the estimated number deaths in the exposed population.

The results of a risk assessment are used by risk managers, such as regulatory agencies, to determine the need for regulation or remediation, and to set discharge limits. The U.S. Environmental Protection Agency (USEPA) currently considers excess individual lifetime cancer mortality risks within the range of 1×10^{-6} (one-in-a-million) to 1×10^{-4} (one-in-ten-thousand) to be acceptable (Federal Register, 1991).

A common approach to the assessment of risk associated with the discharge of a contaminant to the environment is to perform an assessment in two steps. The first step is a screening assessment using simple models and conservative assumptions which results in an overestimate of risk. For discharges identified as presenting potentially significant risks by a screening analysis, more realistic and complex assessments are performed in a second step. In this second step, conservative assumptions and simple models are replaced by best estimates and more sophisticated models.

This paper reports on the first phase of a risk assessment for radium discharged to coastal Louisiana in produced waters. An initial screening-level risk assessment was performed to determine if a more comprehensive and realistic analysis is required. The analysis presented here does not use state-of-the-art models or analytical techniques, but should be viewed as a screening exercise to determine if there is a potential for significant risk.

To perform a risk assessment for radium in produced water the major transport pathways, exposure routes and receptors of concern were identified. Figure 1 summarizes the potentially important transport pathways and exposure routes for radium discharged in produced water. The ingestion of contaminated fish and shellfish is expected to be the most significant exposure route, because people spend only a small amount of time in contact with coastal water, and because radium is known to accumulate in fish and shellfish. The important receptors for radium discharged in produced water are people ingesting a large amount of fish and shellfish harvested near a produced water outfall. People subsisting on locally harvested fish and shellfish and workers fishing from the platforms are represented by the maximally exposed individual -- the hypothetical person ingesting a large amount of seafood harvested near an outfall.

Figure 1. Major transport and exposure pathways to man from radium discharged in produced water.

In the screening-level analysis described here, exposures to man from Ra-226 and Ra-228 were estimated for water concentrations of radium representative of produced water outfalls and for the levels measured in organisms in a study performed by Continental Shelf Associates (CSA, 1991). For comparison, risks associated with background radium concentrations were also calculated. Average individual lifetime risks and total population risks were estimated using simple models and conservative assumptions. This screening-level assessment represents a conservative analysis,

involving a number of simplistic assumptions that necessarily result in an over-estimate of the risk associated with the discharge of radium in produced water.

ESTIMATION OF INDIVIDUAL LIFETIME RISK

Data Sets Used in the Assessment

The assessment of individual risk was performed using two sets of data to describe radium concentrations in water and in seafood resulting from produced water discharges. The first data set is from a field study of three produced water outfalls and six background stations in coastal Louisiana (CSA, 1991). The outfalls included in this field study did not cover the entire range of potential discharges to coastal Louisiana, and five potential (or modeled) discharge scenarios were included in this assessment. These two data sets are described in more detail below.

CSA Study: Three produced water discharge platforms and six reference stations were sampled in this study. Ra-226 and Ra-228 concentrations were measured in the discharged produced water and at stations located 25 and 50 feet from the outfalls in three directions. Radium concentrations were also measured in sediment and biological samples from each station. The three outfalls were located in canals along the Louisiana coast. At these stations, there were produced water discharges for several years before sampling, with discharge rates typical of produced water discharges in coastal Louisiana (3,000 to 5,000 bbl/day).

Potential Discharge Scenarios: For all of these modeled scenarios, it was assumed that the concentration of Ra-226 was equal to the concentration of Ra-228 in each discharge. To represent background conditions, two zero discharge scenarios were included, with assumed Ra-226/Ra-228 concentrations in water of 0.1 and 1.0 pCi/l. The three discharge scenarios included in the assessment were 30 pCi/l, 500 pCi/l and 2,000 pCi/l. The 2,000 pCi/l discharge represents the very few high discharge concentration outfalls in coastal Louisiana, while the 500 and 30 pCi/l discharges are more typical.

Steps in the Assessment

The calculation of the individual lifetime cancer risk associated with the discharge of radium in produced water involved the following steps (Figure 2): 1) estimate the concentration of Ra-226 and Ra-228 in coastal water; 2) estimate the concentration of Ra-226 and Ra-228 in fish and shellfish; 3) estimate the amount of fish and shellfish that could be consumed by individuals; 4) calculate the amount of Ra-226 and Ra-228 consumed by individuals in seafood and 5) calculate the individual lifetime risk associated with the estimated radium intake in fish and shellfish. These steps in the risk assessment are described in detail below.

Figure 2. Steps in estimating individual lifetime risk.

Radium Concentrations in Water

Field Study: For the data collected by CSA (1991), radium concentrations in water are not needed for a risk assessment study because the concentration of radium in fish and shellfish was measured. The average concentrations in water sampled 50 feet from the outfalls are given in Table 2.

Potential Discharge Scenarios: The five potential (or modeled) scenarios used in the analysis require the estimation of water concentrations to calculate concentrations in aquatic organisms used for food. The concentrations in water resulting from the three potential discharge concentrations (30, 500 and 2,000 pCi/l) were calculated assuming a dilution factor of 100 within 50-100 feet of the outfall. The use of a dilution factor of 100 is a reasonable, but conservative assumption, because most fish and shellfish will be harvested further than 100 feet from a discharge point. A dilution factor of 100 applied to the three discharge scenarios described above (30, 500 and 2,000 pCi/l) results in water concentrations (of both Ra-226 and Ra-228) of 0.3, 5 and 20 pCi/l (Table 3). Assumed concentrations in water for the two zero discharge, background scenarios were 0.1 and 1.0 pCi/l.

Table 2. Values used in calculation of individual risk for field data from the CSA (1991) study. Ra-226 and Ra-228 concentrations in discharge, water and aquatic organisms.

Station	Discharge Ra-226/Ra-228 (pCi/l)	Water Conc. ¹ Ra-226/Ra-228 (pCi/l)	Fish ² Ra-226/Ra-228 (pCi/g)	Oysters ³ Ra-226/Ra-228 (pCi/g)	Crustaceans ⁴ Ra-226/Ra-228 (pCi/g)
Site 1	228.9/383.0	0.43/0.93	0.014/0.005	0.007/0.003	0.073/0.094
Site 2	110.6/244.4	0.52/0.22	0/0.022	0.008/0.011	0.068/0.025
Site 3	251.9/254.9	0.91/4.0	0.041/0.012	NS/NS	0.125/0.243
Background 1a	0/0	0.25/0.15	NS/NS	0.001/0.036	0.014/0.004
Background 1b	0/0	0.2/0	0.005/0.021	0.004/0.011	0.024/0.025
Background 2a	0/0	0.7/0	0.002/0.030	0.004/0.003	NS/NS
Background 2b	0/0	0.5/0	0.031/0.127	0.001/0.01	0.069/0.033
Background 3a	0/0	0.7/3.3	0.018/0.058	NS/NS	0.016/0.058
Background 3b	0/0	0.7/10.3	0.030/0.017	NS/NS	0.077/0.045

NS: no sample

¹ average of measured concentration at three stations, each 50 feet from discharge; for reference samples value is average of two samples taken at station.

² all fish samples were Cynoscion spp. (seatrout).

³ all oyster samples were Crassostrea virginica.

⁴ crustacean samples at stations 1 and 3 were Penaeus spp. (shrimp), crustaceans at station 2 were Callinectes spp. (crab).

Table 3. Values used in calculation of individual risk for five potential discharge/water concentration scenarios. Ra-226 and Ra-228 concentrations in discharge, water and aquatic organisms.

Scenario	Discharge (pCi/l)	Water Conc. ¹ (pCi/l)	Fish ² (pCi/g)	Molluscs ² (pCi/g)	Crustaceans ² (pCi/g)
Low Background	0	0.1	0.01	0.01	0.01
High Background	0	1.0	0.1	0.1	0.1
Low Discharge	30	0.3	0.03	0.03	0.03
High Average Discharge	500	5.0	0.5	0.5	0.5
High Discharge	2000	20.0	2.0	2.0	2.0

¹ assumes dilution factor of 100 within 50-100 feet of the outfall.

² calculated using concentration factor method, CF= 100.

Concentration of Radium in Aquatic Organisms Used For Food

Field Study: The data set extracted from CSA (1991) includes measurements of Ra-226 and Ra-228 concentrations in fish, oysters and crustaceans sampled within 50 feet of the outfalls and at the six background stations. These data are given in Table 2.

Potential Discharge Scenarios: The concentrations of Ra-226 and Ra-228 in fish, molluscs and crustaceans were calculated for the five potential scenarios described above (water concentrations of 0.1, 1, 0.3, 5 and 20 pCi/l) using the concentration factor method. For the purposes of this screening-level assessment, the conservative IAEA Concentration Factors (100 for fish, molluscs and crustaceans) were used. The estimated concentrations of Ra-226 and Ra-228 in fish, molluscs and crustaceans for the five potential discharge/water concentration scenarios are given in Table 3.

Amount of Radium Ingested in Seafood

To calculate risk from ingestion of radium in seafood, the amount of seafood consumed by an individual per year is needed. Food consumption patterns vary among individuals and with age and geographic location. This study used intake rates from a survey commissioned by the National Marine Fisheries Service in 1973-1974 and described in Rupp et al. (1980). Intake rates for people living in the West South Central Region of the United States (Arkansas, Louisiana, Oklahoma and Texas) were used in the assessment presented here.

Rupp et al. (1980) report consumption rates for three age groups (1-11 years, 12-18 years, and 19-98 years) and for three types of seafood (freshwater fish, salt water fish and shellfish). A regional distribution of shellfish consumed by species (i.e. percent of the total of each species that is consumed by each U.S. region) is presented in Rupp et al. (1980). These data were used to estimate the percent of shellfish consumption represented by molluscs (23.76%) and by crustaceans (76.24%) for the West South Central Region. Table 4 gives the intake rates (kg/year) for the three age groups, calculated from the data in Rupp et al. (1980).

Intake levels for adults (19-98 years) were used in this analysis. Three intake rates were used in this preliminary assessment: the maximum intake rate, the average intake rate for fish/shellfish consumers, and the average intake rate for the whole

population (Table 4). In all cases it was conservatively assumed that 50% of a person's entire seafood intake was harvested near a produced water outfall.

Table 4. Marine fish and shellfish consumption in Arkansas, Louisiana, Oklahoma and Texas (kg/year).^{1,2}

Age Group (years)	Type	Maximum Consumer	Consumer Average	Population Average
1-11 (n = 510)	fish	15.12	1.77	1.52
	molluscs	2.73	0.46	0.14
	crustaceans	8.78	1.47	0.44
12-18 (n = 194)	fish	28.62	2.76	2.40
	molluscs	3.35	0.56	0.17
	crustaceans	10.77	1.82	0.53
19-98 (n = 1424)	fish	31.20	4.03	3.57
	molluscs	5.93	0.84	0.33
	crustaceans	19.02	2.71	1.07

¹ Data derived from Rupp et al., 1980.

² Shellfish divided into molluscs and crustaceans by percentages derived from data in Rupp et al., 1980 for entire United States (23.76% molluscs, 76.24% crustaceans).

The amount of radium consumed in seafood per day was calculated as follows:

$$\begin{array}{ccccccc} \text{Consumption} & = & \text{Food Conc.} & \times & 1000 & \times & \text{Intake} & \times & 1/365 & & (2) \\ (\text{pCi/day}) & & (\text{pCi/g}) & & (\text{g/kg}) & & (\text{kg/year}) & & (\text{year/days}) & & \end{array}$$

Using the intake rates described above, Ra-226 and Ra-228 consumption rates in units of pCi/day were calculated for the concentrations of radium measured in fish and shellfish in the CSA (1991) study, and for the estimated levels of radium in seafood for the five potential discharge scenarios.

Calculation of Individual Lifetime Risk

Conservative, upper bound estimates of individual lifetime risk were calculated using the USEPA risk factors (Ra-226: 2.2×10^{-6} per pCi/day lifetime intake, Ra-228: 1.9×10^{-6} per pCi/day lifetime intake). Individual lifetime risk estimates were calculated separately for Ra-226 and Ra-228 and then summed for each exposure scenario as follows:

$$\begin{array}{l} \text{Individual Lifetime Risk} = [\text{Ra-226 Consumption (pCi/day)}] \times [\text{Ra-226 Risk Factor}] \\ + [\text{Ra-228 Consumption (pCi/day)}] \times [\text{Ra-228 Risk Factor}] \end{array} \quad (3)$$

Table 5 gives the estimates of individual lifetime risk for ingestion of Ra-226 and Ra-228 in seafood for the three produced water discharges and six background stations sampled in the CSA (1991) study. No individual lifetime risk estimates based on the CSA (1991) data exceeded a level of 1×10^{-4} . Levels of 1×10^{-5} were exceeded for Sites 1 and 3 for the maximum consumer (Table 5). Levels of 1×10^{-5} were also exceeded for the hypothetical maximum consumer at three of the six reference sites.

Table 5. Individual lifetime risk estimates for consumption of fish, molluscs and crustaceans harvested from waters with enhanced levels of radium - estimates based on data from a field study in coastal Louisiana (CSA, 1991).

	Water Concentration Ra-226/Ra-228 (pCi/l)	-----Lifetime Risk-----		
		Maximum Consumer	Consumer Average	Population Average
Site 1	228.9/383.0	1.1E-5	1.5E-6	7.1E-6
Site 2	110.6/244.4	7.7E-6	1.1E-6	5.7E-7
Site 3 ¹	251.9/254.9	2.4E-5	3.3E-6	1.6E-6
Background 1a	0.25/0.15	1.6E-6	2.2E-7	8.8E-8
Background 1b	0.2/0	5.1E-6	6.9E-7	4.1E-7
Background 2a	0.7/0	2.7E-6	3.6E-7	3.1E-7
Background 2b	0.5/0	1.9E-5	2.5E-6	1.8E-6
Background 3a	0.7/3.3	1.0E-5	1.4E-6	9.5E-7
Background 3b	0.7/10.3	1.1E-5	1.5E-6	8.6E-7

¹ No mollusc samples at station 3, estimates based on concentrations of radium in fish and crustaceans only.

Table 6 presents individual lifetime risk estimates for the five potential discharge scenarios. Individual lifetime risk estimates based on the potential discharge scenarios exceeded 1×10^{-4} for the maximum consumer at the two higher discharge sites (500 pCi/l and 2000 pCi/l). A risk of 1×10^{-5} was exceeded for the maximum consumer/high background scenario, for the maximum consumer at the low discharge outfall (30 pCi/l), and for all intake rates at the two high discharge outfalls (500 and 2,000 pCi/l).

Table 6. Individual lifetime risk estimates for consumption of fish, molluscs and crustaceans harvested from waters with enhanced levels of radium - estimates based on analysis of five potential discharge/water concentration scenarios.

Scenario	Discharge Water Conc ¹		-----Lifetime Risk-----		
	(pCi/l)	(pCi/l)	Maximum Consumer	Consumer Average	Pop. Average
Low Background	0	0.1	3.2E-6	4.3E-7	2.8E-7
High Background	0	1.0	3.2E-5	4.3E-6	2.8E-6
Low Discharge	30	0.3	9.5E-5	1.3E-6	8.4E-6
High Average Discharge	500	5.0	1.6E-4	2.1E-5	1.4E-5
High Discharge	2000	20.0	6.3E-4	8.5E-5	5.6E-5

¹ water concentration at 50 to 100 feet from the outfall

These risk estimates are based on the following assumptions: (1) radium discharged in produced water is reduced by a factor of 100 before coming in contact with edible fish and shellfish; (2) an individual gets one-half of their yearly fish and shellfish from near (i.e. where the dilution factor reaches 100, probably within 100 feet) a produced water outfall for their entire lifetime; (3) a concentration factor of 100 can be used to estimate the concentration of radium in fish and shellfish; and (4) the USEPA risk factors for radium accurately describe the risk associated with the ingestion of small amounts of radium over a lifetime.

ESTIMATION OF POPULATION RISK

A conservative, upper-bound estimate of the population risk associated with the ingestion of radium from produced waters was calculated using simple models and assumptions. To estimate total population risk several calculations were needed -- the "average" increase in radium concentrations in coastal Louisiana; the resulting "average" concentration of radium in fish and shellfish; and the amount of fish and shellfish ingested from the area. The steps in the calculation of population risk are outlined in Figure 3.

Figure 3. Steps in estimating population risk.

Radium Concentrations in Water

A simple steady state box model (IAEA, 1982) was used to estimate the increase in Ra-226 and Ra-228 concentrations in the coastal zone of Louisiana resulting from the discharge of radium in produced water. All radium discharged into the coastal zone was assumed to remain in the water column. The model assumes a constant input of radium and complete mixing within a given volume. The steady state concentration of radium in water can be estimated as:

$$C = Q / K_e V \quad (4)$$

where:

C = the change in radium water concentration (pCi/l)

Q = the radium discharge rate (pCi/day)

V = the volume of water in the Louisiana coastal zone (l)

K_e = the fractional loss rate of water from the mixed volume (day⁻¹)

The removal constant K_e is estimated as:

$$K_e = q + r/V \quad (5)$$

where:

q = the decay constant

r/V = the fractional loss rate of water from the mixed volume.

In tidally influenced coastal seas, V may be described by the tidal excursion, and r/V by the net water movement (IAEA, 1982). K_e can also include the loss of radium to the sediments, based on the distribution coefficient K_d .

A conservative estimate (i.e. small) of the volume of water in the Louisiana coastal zone was developed based on the area of surface water in the coastal zone of Louisiana (2631 km², Department of Commerce, 1984), and an assumed depth of 3 meters. These assumptions result in a calculated volume of 7.9×10^{13} liters. The fractional loss rate used was 0.015. This value is based on studies of the Barataria and Terrebonne-Timbalier Basins in Louisiana reported in Boesch and Rabalais (1989).

The rate of Ra-226 and Ra-228 discharged into the coastal zone of Louisiana (Q) was estimated by summing the discharges (pCi/day) for all of the stations in the database compiled by the State of Louisiana. These totals were 4.39×10^{10} pCi/day for Ra-226 and 4.83×10^{10} pCi/day for Ra-228. The increase in Ra-226 and Ra-228 concentrations due to produced water discharges (C) was calculated using the box model and parameters described above. The resulting increases in radium concentrations were 0.37 pCi/l for Ra-226 and 0.41 pCi/l for Ra-228.

Concentration of Radium in Aquatic Organisms Used For Food

The "average" concentration of Ra-226 and Ra-228 in fish and shellfish harvested in coastal Louisiana was estimated using the concentration factor method. The IAEA values (IAEA, 1982) (100 for fish, molluscs and crustaceans) were used in this analysis. The "average" radium concentrations in fish, molluscs and crustaceans were calculated for 1) the estimated increase in water concentration due to produced water discharges (Ra-226: 0.37 pCi/l, Ra-228: 0.41 pCi/l); 2) a low estimate of background radium levels (0.1 pCi/l for both Ra-226 and Ra-228) and; 3) a high estimate of background radium concentrations (1.0 pCi/l for both Ra-226 and Ra-228). The estimated average concentration in fish and shellfish for these water concentrations are given in Table 7.

Amount of Radium Ingested in Seafood

To estimate the number of excess cancers resulting from ingestion of radium, the amount of fish and shellfish harvested and ingested per year from coastal Louisiana is needed. The catch in millions of pounds live weight for Louisiana in 1989 was 1.23×10^9 pounds (Department of Commerce, 1990). Some of this catch was from offshore -- this analysis assumed that 50% of the reported catch for Louisiana was harvested in coastal waters. In 1989, 73.3% of the fish and shellfish harvested in the United States was used for human food (Department of Commerce, 1990). Not all of the fish and shellfish catch is consumed -- the value for Louisiana reported above includes fish bones and skin but not clam or oyster shells. In this analysis, it was assumed that 75% of the fish and shellfish used for human food was actually consumed. The amount of fish and shellfish consumed per day was calculated as follows:

$$(1.23 \times 10^9 \text{ lbs/year}) \times (0.5 \text{ inshore}) \times (0.73 \text{ for food}) \times (0.75 \text{ eaten}) \\ \times (453.6 \text{ g/lb}) (1/365 \text{ year/days}) = 4.2 \times 10^8 \text{ g/day} \quad (6)$$

The amount of radium ingested in fish and shellfish (pCi/day) was calculated by multiplying the amount ingested in the region over a year (4.2×10^8 grams/day) times the "average" concentration of Ra-226 and Ra-228 in fish and shellfish (pCi/g) (Table 7).

Table 7. Calculated average radium concentrations in seafood and amount ingested.

	Ra-226			Ra-228		
	water (pCi/l)	food ¹ (pCi/g)	ingested (pCi/d)	water (pCi/l)	food ¹ (pCi/g)	ingested (pCi/d)
Produced Water	0.37	0.037	1.6E7	0.41	0.041	1.7E7
Low Background	0.1	0.01	4.2E6	0.1	0.01	4.2E6
High Background	1.0	0.1	4.2E7	1.0	0.1	4.2E7

¹ calculated using the concentration factor method, CF = 100.

Calculation of Population Risk

Conservative, upper bound estimates of population risk were calculated using the USEPA risk factors (Federal Register, 1991) of 2.2×10^{-6} per pCi/day lifetime intake for Ra-226 and 1.9×10^{-6} per pCi/day lifetime intake for Ra-228. The number of excess cancers expected over a 70 year lifetime were calculated as:

$$\text{Population Risk} = \text{Consumption (pCi/day)} \times \text{Risk Factor} \quad (7)$$

The resulting estimates of excess cancers per year of operation are given in Table 8. The risk to the individual associated with the increase in radium predicted by this analysis (0.37 pCi/l Ra-226; 0.41 pCi/l Ra-228) is 2.5×10^{-5} assuming the maximum consumption rate (Table 4) and 2.2×10^{-6} assuming the average population consumption rate.

Table 8. Estimated excess cancers per lifetime from radium in coastal Louisiana waters .

	Ra-226		Ra-228		Total cancers
	pCi/l	cancers	pCi/l	cancers	
Produced Water	0.37	35	0.41	32	67
Low Background	0.1	9	0.1	8	17
High Background	1.0	92	1.0	80	172

← at current levels of produced water discharge

DISCUSSION

Using the conservative assumptions outlined above, a level of risk which could be considered significant (greater than 1×10^{-4}) was estimated for the person consuming the most seafood under the two highest discharge scenarios (500 and 2000 pCi/l). No risk estimates for samples taken at three coastal discharge sites exceeded 1×10^{-4} .

Based on a simple, conservative analysis, the total number of excess cancers expected over a 70 year lifetime from Ra-226 and Ra-228 discharged to coastal Louisiana

waters is 67. A similar analysis, using a range of possible background concentrations (0.1 - 1.0 pCi/l) predicted from 17 to 172 excess cancers from background radium in the region. The major uncertainties and conservatisms in this screening-level analysis are:

1. The concentration of radium in water and the geographic distribution of contaminated shellfish. The analysis of individual risk used concentrations likely to be measured at the outfall of a produced water discharge when, in fact, considerable dilution occurs with distance from the discharge point. A reduction in the radium concentrations in fish and shellfish also occurs with increasing distance. The concentration of radium in the water in which fish and shellfish are harvested is critical to the estimation of risk. For the calculation of population risk, a simple box model was used that assumed complete mixing of all discharged radium, and a resultant "average" concentration of radium in fish and shellfish harvested from the region. In fact, radium concentrations in water and in fish and shellfish are variable over the area.
2. The concentration factor used to calculate the concentration of radium in fish, molluscs and crustaceans. Commonly used concentration factors are higher than those derived from the CSA (1991) data set. The concentration factor used in the analysis has a large effect on the resulting risk estimates. Conservative IAEA concentration factors were used in this assessment, which probably resulted in an overestimate of the concentration of radium in food.
3. The distribution of intake rates and the percent of consumed fish and shellfish that is radium contaminated. This analysis assumed that the maximally exposed individual harvested one-half of his seafood from near a produced water outfall. These estimates of intake probably overestimate the amount of fish and shellfish harvested near an outfall even for individuals subsisting on locally harvested seafood.
4. The risk factors for radium. This screening-level analysis used the USEPA risk factors for Ra-226 and Ra-228 (Federal Register, 1991). These risk factors overestimate the health risks associated with exposure to small amounts of radium.

Because of the many conservative assumptions incorporated into this screening-level analysis, it can be concluded that the risks associated with the discharge of produced water to coastal Louisiana are small. The results of this study do, however, suggest the need for a more detailed analysis of the potential risks to individuals subsisting on locally harvested fish and shellfish which may be harvested near a produced water outfall. A more detailed, comprehensive assessment of the risks to this population will be performed.

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