Natural radiation dose
to *Gammarus* from Hudson River (*)

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ABSTRACT

The purpose of this investigation is to evaluate the natural radiation dose rate to whole body and components of the *Gammarus* species, a zooplankton which occurs in the Hudson River among other places, and to compare the results with the upper limits of dose rates from man-made sources. The alpha dose rates to the exoskeleton and soft tissues are about 10 times the average alpha dose rate to the whole body, assuming uniform distribution of ^{226}Ra. The natural alpha radiation dose rate to *Gammarus* represents only about 5 p. cent of the total natural dose to the organism, i. e., 492 mrad/yr. The external dose rate due to ^{40}K, ^{238}U plus daughters and ^{232}Th plus daughters accumulated in the sediments comprise 91 p. cent of that total natural dose rate, the remaining percentage being due to natural internal beta emitters and cosmic radiation. Man-made sources can cause an external dose rate up to 224 mrad/yr, which comprises roughly 1/3 of the total dose rate (up to 716 mrad/yr; natural plus man-made) to the *Gammarus* of Hudson River in front of Indian Point Nuclear Power Station. However, in terms of dose-equivalent the natural sources of radiation would contribute more than 75 p. cent of the total dose to *Gammarus*.

RÉSUMÉ

Le but de cette recherche est la détermination de la dose d'irradiation naturelle pour l'organisme entier, ainsi que pour certains organes de l'espèce *Gammarus* — un zooplancton du fleuve Hudson et d'autres milieux aquatiques — et la comparaison de ces résultats avec les limites supérieures des doses dues aux sources artificielles. Les doses alpha pour l'exosquelette et pour les tissus mous sont environ 10 fois supérieures à celles pour le corps entier, avec

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l'hypothèse d'une distribution uniforme de ^{226}Ra. La dose d'irradiation naturelle alpha pour *Gammarus* correspond seulement à environ 5 p. cent de la dose totale d'irradiation naturelle (492 mrad/an). La dose d'irradiation externe due à ^{40}K, à ^{238}U et à ^{232}Th y compris leurs descendants accumulés dans les sédiments correspond à 91 p. cent de la dose totale; le pourcentage restant correspond aux émetteurs bêta naturels internes, et au rayonnement cosmique. Les sources artificielles peuvent être responsables d'une dose externe allant jusqu'à 224 mrad/an, laquelle comprend environ 1/3 de la dose totale (due aux sources naturelles et artificielles et dont la valeur peut varier jusqu'à 716 mrad/an) pour *Gammarus* vivant dans le fleuve Hudson en face de la centrale nucléaire d'Indian Point. Cependant, en terme d'équivalents de doses, les sources naturelles contribueraient pour plus de 75 p. cent de la dose totale pour le *Gammarus*.

INTRODUCTION

The investigation of the radiation dose to aquatic organisms under laboratory conditions and in the natural environment has been recognized by TEMPLETON *et al.* (1971) as an important subsidizer to establish a baseline for studies of the effects of radiation. Two main difficulties are related to the calculations of the dose rate from radionuclides absorbed by or adsorbed on aquatic organisms in general, and plankton in particular, as follows: (i) radionuclides are seldom distributed uniformly throughout the organisms; and (ii) the wide variation in the energy and type of emissions.

Using conventional dosimetry, CHERRY has assumed that 50 p. cent of the energy of alpha particles emitted in diatoms was absorbed within the organisms, without consideration neither of the distribution of alpha emitters nor the geometry of the phytoplankton diatom [3]. Later, SHANNON and CHERRY and SHANNON [18, 19] have assumed, in new dosimetric estimations, that 25 p. cent of the total energy of alpha particles emitted in a phytoplankton would be absorbed, while for the zooplankton nearly 100 p. cent would be absorbed, assuming in both cases undefined geometries for the organisms and uniform distribution of alpha emitters. Those somewhat arbitrary assumptions led to the indication that the natural radiation dose received by plankton might be higher than the estimations (i. e., between 40 and 620 mrad/yr from deep sea sediments) made earlier by FOLSOM and HARLEY who assumed that the internal alpha dose rate to plankton would be negligible [5]. However, not until recently the first dosimetric model was introduced by WOODHEAD, to calculate the radiation dose to plankton [21].

The dosimetric model developed by WOODHEAD assumes that all phytoplankton species are represented by a sphere of unit density tissue 50 μm density tissue 0.5 cm long and 0.2 cm diameter. Although WOODHEAD's model assumes these generalized geometries for phyto and zooplankton, it fails to discuss distributions of alpha emitters other than the uniform distribution throughout the entire volume of the geometric figures adopted. As a consequence, the dosimetric model developed by WOODHEAD is helpful to

make general comparisons, but it is inadequate to calculate the alpha dose rate to any particular species of plankton.

A dosimetric model which takes into account the distribution of alpha emitters with aid of quantitative autoradiograph is described elsewhere [15], and it is applied here to calculate the internal alpha dose rate to selected components of *Gammarus*. The total (internal plus external) natural dose rate is calculated from direct measurements and then compared with the upper limits for external dose rate from man made sources in the area of the Hudson River where *Gammarus* have been collected.

MEAN ALPHA ENERGY AVAILABLE POR DEPOSTION IN ORGANISMS FOLLOWING ACCUMULATION OF ^{228}Ra AND ^{226}Ra

The capacity of plankton to concentrate natural occurring radionuclides is reviewed elsewhere [16]. In particular, ^{226}Ra, ^{228}Ra have higher concentrations in plankton relatively to their concentrations in water. Tables I and II present the average concentrations of selected radionuclides from natural (including ^{226}Ra, ^{228}Ra, and ^{228}Th) and man-made origins in *Gammarus* of Hudson River.

The natural alpha dose rate to an organism depends, of course, on the alpha energy available for deposition within that organism. On the other hand, the alpha energy available for deposition is a function of the fraction of the gaseous radionuclides of the natural series, i. e., ^{220}Rn (thoron) and ^{222}Rn (radon) that escape from the organism, because they are both alpha emitters themselves and precursors of other alpha emitters as can be seen on Tables III and IV. Accordingly, for dosimetric purposes, it is necessary to know the mean alpha energy, $\overline{E}_{\alpha T}$ and $\overline{E}_{\alpha R}$, available for deposition within the organisms following uptake of ^{228}Ra and/or ^{228}Th, and ^{226}Ra respectively, if the dosimetry is based on counting alpha tracks in autoradiographs [15].

The expression for $\overline{E}_{\alpha T}$ may be written as follows:

$$\overline{E}_{\alpha T} = \sum_{i=1}^{2} E_{\alpha T - i} + (1 - f_{Tn}) \sum_{j=3}^{6} E_{\alpha T - j} \qquad (1)$$

where $E_{\alpha T - i}$ and $E_{\alpha T - j}$ are the average alpha energies per disintegration of each radio-nuclide relevant in the ^{228}Ra chain of daughters, taking into account the frequency of emission for the particular energies; and f_{Tn} is the fraction of thoron gas escaping from the organism.

The half-life of thoron is only 55.3 s and the biological mechanisms of release ordinarily last hours, therefore, it is reasonable to hypothesize that f_{Tn} may be considered negligible, although little is still known about the amount of thoron and radon gases produced that escape from aquatic organisms after accumulation of ^{228}Ra and ^{226}Ra, respectively. Thus, substituting $f_{Tn} \simeq 0$ into equation (1), the average alpha energy, $\overline{E}_{\alpha T}$, becomes

$$\overline{E}_{\alpha T} \simeq 31.9\,\text{MeV}. \qquad (2)$$

The rationale behind the approximation $f_{Tn} \simeq 0$ may be reinforced by keeping in mind that the exhalation of thoron produced in human beings depends on the nature of the internal contamination, and it ranges from 0.12 p. cent to 12 p. cent [7]. The mean alpha energy available for deposition per disintegration of ^{228}Ra and/or ^{228}Th calculated by equation (1) with $f_{Tn} = 0.12$ (i. e., by taking the upper limit of 12 p. cent of thoron escaping) is 28.7 MeV

TABLE I

AVERAGE CONCENTRATIONS OF ^{226}Ra, ^{210}Po AND ^{228}Th AND DAUGHTERS IN GAMMARUS OF HUDSON RIVER, AVERAGE CONCENTRATIONS IN DISTINCT SITES OF THE ORGANISMS, AND α-DOSE RATES

Site	Concentration (pCi/g wet)			α dose rate (μrad/h)	
	^{226}Ra	^{210}Po	^{228}Th	^{226}Ra-^{214}Po	^{226}Ra + Daught. and ^{228}Th + Daught.
Whole body...............	0.047 ± 0.008	0.034 ± 0.004 (^{b})	0.022 ± 0.006	1.2 (^{e}) (11 mrad/yr)	3.1 (^{d}) (27 mrad/yr)
G.I. tract...............	0.517 (^{c})	—	—	13 (^{e})	—
Soft tissue...............	0.0047	—	—	0.12 (^{e})	—
Non-identified organ (^{a}).........	0.362 (^{c})	—	—	9.3 (^{e})	—
Exoskeleton...............	0.018	—	—	0.15 (^{b})	—
Appendages...............	0.007	—	—	0.09 (^{e})	—

(^{a}) Consultation with several marine biologists has not provided positive identification.

(^{b}) Measured in one sample containing 256 mg dry.

(^{c}) Lower limit.

(^{d}) Sum of dose rates calculated by equation (5) plus $\bar{D}_\alpha$ (^{210}Po) = 2.13 × 5.3 C (^{210}Po) plus $\bar{D}_\alpha$ (^{228}Th + daughters) = 2.13 × 31.93 (^{228}Th + daughters).

(^{e}) Calculated by equation (5).

(^{f}) Calculated by equation (6).

(^{g}) Calculated by equation (7).

TABLE II

CONTENTS OF SELECTED NATURAL AND MANMADE RADIONUCLIDES IN GAMMARUS (a) FROM THE HUDSON RIVER AND UPPER LIMITS FOR THE CORRESPONDING β-DOSE RATES (b)

Radionuclide	Concentration pCi/g wet	Contributions due to emissions (c) (μrad/h)/(pCi/g)			Upper limit of β-dose rate μrad/h	μrad/h
		e A	c. e.	β decay		
^{40}K	0.48 ± 0.08	0.000 5	–	1.069	0.51 ± 0.09	
^{226}Ra	0.047 ± 0.008 (d)	0.003 8	0.181	1.9	0.10 ± 0.02	0.71 ± 0.09 natural (6.2 mrad/yr)
^{228}Ra-^{228}Ac	0.061 ± 0.015	0.000 4	0.126 8	0.887	0.06 ± 0.02	
^{228}Th + Daught	0.022 ± 0.006	0.018	0.218 6	1.711	0.04 ± 0.01	
^{137}Cs	0.032 ± 0.005	0.001	0.127 7	0.402	0.017 ± 0.003	
^{54}Mn	0.024 ± 0.006	0.008 5	0.000 4	–	0.000 2 ± 0.000 1	0.023 ± 0.004 manmade (0.2 mrad/yr)
^{60}Co	0.019 ± 0.005	< 0.000 1	0.000 7	0.206	0.004 ± 0.001	
^{95}Zr-Nb	0.009 ± 0.006	0.000 2	0.008 5	0.252	0.002 ± 0.002	

(a) All results with exception of those for ^{226}Ra were obtained by γ-spectrometry of the ashes of over 1×10^4 individual organisms.

(b) β-dose rates were calculated assuming total absorption of energy within the organisms and taking into account the average β decay energy plus the contributions of Auger and conversion electrons whenever these contributions were significant.

(c) The contributions due to Auger electrons (e A), conversion electrons (c. e.) and β-decay were calculated from [13].

(d) Average of measurements made by gamma spectrometry and by radon-emanation technique in four samples.

which represents about 90 p. cent of the mean alpha energy available for deposition with total thoron retention.

The dose rate to *Gammarus* due to concentration of ^{226}Ra is mainly due to the alpha disintegration of ^{226}Ra itself plus the alpha disintegration of its daughter products through ^{214}Po, since the ingrowth of ^{210}Po is slowed by the long half-life of ^{210}Pb (21 years). Ana-

TABLE III

URANIUM SERIES

Radionuclide	Half-life	Energies of emissions (MeV) and intensities (%)		
		α	β	γ
^{238}U	4.51×10^9 yr	4.15 (25) (*) 4.20 (75)	–	–
α↓				
^{234}Th	24.1 d	–	0.103 (21) 0.193 (79)	0.063 (3.5) 0.093 (4)
β↓				
^{234m}Pa	1.17 m	–	2.29 (98)	0.765 (0.30) 1.001 (0.60)
γ↓(0.13)				
^{234}Pa	6.75 h	–	0.53 (66) 1.13 (13)	0.100 (50) 0.70 (24) 0.90 (70)
β (99) β↓				
^{234}U	2.47×10^5 yr	4.72 (28) 4.77 (72)	–	0.053 (0.2)
α↓				
^{230}Th	8.0×10^4 yr	4.62 (24) 4.68 (76)	–	0.068 (0.6) 0.142 (0.07)
α↓				
^{226}Ra	1602 yr	4.60 (6) 4.78 (95)	–	0.186 (4)
α↓				
^{222}Rn	3.823 d	5.49 (100)	–	0.510 (0.07)
α↓				
^{218}Po	3.05 m	6.00 (~ 100)	0.33 (~ 0.019)	–
β↓(0.02)				
^{218}At	~ 2 s	6.65 (6) 6.70 (94)	? (~ 0.1)	–
α↓ (~ 100)				
^{214}Bi	19.7 m	5.45 (0.012) 5.51 (0.008)	1.0 (23) 1.51 (40) 3.26 (19)	0.609 (47) 1.120 (17) 1.764 (17)
β (99.98) (0.02) α				
^{214}Po	164 s	7.69 (100)	–	0.799 (0.014)
^{210}Tl	1.3 m	–	1.3 (25) 1.9 (56) 2.3 (19)	0.296 (80) 0.795 (100) 1.31 (21)
α (100) β				
^{210}Pb	21 yr	3.72 (2×10^{-6})	0.016 (85) 0.061 (15)	0.047 (4)
β↓				
^{210}Bi	5.01 d	4.65 (7×10^{-5}) 4.69 (5×10^{-5})	1.161 (~ 100)	–
β↓(~ 100)				
^{210}Po	138.4 d	5.305 (100)	–	0.803 (0.001 1)
α↓(0.0001 3)				
^{206}Ti	4.19 m	–	1.571 (100)	–
β↓				
^{206}Pb	Stable	–	–	–

(*) Numbers between brackets indicate intensity in p. cent. Based on data from [9].

TABLE IV

THORIUM SERIES

Radionuclide	Half-life	Energies of emissions (MeV) and intensities (%)		
		α	β	γ
232Th	1.41×10^{10} yr	3.95 (24) (a) 4.01 (76)	–	–
α↓				
228Ra	6.7 yr	–	0.055 (100)	–
β↓				
228Ac	6.13 h	–	1.18 (35) 1.75 (12) 2.09 (12)	0.34 (15) 0.908 (25) 0.96 (20)
β				
228Th	1.910 yr	5.34 (28) 5.43 (71)	– –	0.084 (1.6) 0.214 (0.3)
α↓				
224Ra	3.64 d	5.45 (6) 5.68 (94)	–	0.241 (3.7)
α↓				
220Rn	5 s	6.29 (100)	–	0.55 (0.07)
α↓				
216Po	0.15 s	6.78 (100	–	–
α↓				
212Pb	10.64 h	– –	0.346 (81) 0.586 (14)	0.239 (47) 0.300 (3.2)
β↓				
212Bi	60.6 m	6.05 (25) 6.09 (10)	1.55 (5) 2.26 (55)	0.040 (2) 0.727 (7)
β↓(64)				
212Po	304 ns	8.78 (100)	–	1.620 (1.8)
α↓(36)				
208Ti	3.10 m	–	1.28 (25) 1.52 (21) 1.80 (50) –	0.511 (23) 0.583 (86) 0.860 (12) 2.614 (100)
α β				
208Pb	Stable	–	–	–

(a) Numbers between brackets indicate intensity in p. cent. Based upon data from [9].

logically to the preeceding case, the mean alpha energy, $\bar{E}_{\alpha R}$ available for deposition within the organism following uptake of 226Ra may be expressed as follows:

$$\bar{E}_{\alpha R} = E_{\alpha R - 1} + (1 - f_{Rn}) \sum_{k=2}^{4} E_{\alpha R - k} \qquad (3)$$

where $E_{\alpha R - 1}$ and $E_{\alpha R - k}$ are the average alpha energies per disintegration of 226Ra and its daughter products through 214Po, respectively, taking into account the frequency of emissions for the particular energies; and f_{Rn} is the fraction of radon gas escaping from the organism.

The half-life of radon gas is 3.82 days, hence the reasoning made earlier for thoron cannot be applied for radon. Therefore, the fraction, f_{Rn}, of radon gas produced inside a *Gammarus* that escapes from the organism ought to be known in order to calculate the mean alpha energy available for deposition within the organism after accumulation of 226Ra. Laboratory experiments were set up to determine the fraction, f_{Rn}, of radon that escapes from *Gammarus* previously labelled with 226Ra [14]. The mean fraction of radon escaping from

the labelled organism is $\bar{f}_{Rn} = 0.62 \pm 0.09$ [1] with a range from 0.425 ± 0.003 to 0.84 ± 0.01.

Thus substituting $\bar{f}_{Rn} = 0.62$ in place of f_{Rn} into equation (3), the mean energy, $E_{\alpha R}$, available for deposition in *Gammarus* following uptake of ^{226}Ra is:

$$\bar{E}_{\alpha R} = 12.1 \,\text{MeV}. \tag{4}$$

The amphipod *Gammarus* occuring in the Hudson River

The macrozooplankton, *Gammarus*, most usually collected in the Hudson River estuary is *G. tigrinus* [8]; however, *G. fasciatus* and *G. daiberi* are also likel yto occur in the Hudson riber. According to Bousfield, strictly fresh water amphipods like *G. fasciatus* may be washed into estuaries or even into marine habitats, but oligohaline brackish amphipods as *Gammarus tigrinus* and *Gammarus daiberi*, for example are seldom found in full marine salinities [1].

Photograph of a typical *Gammarus* from Hudson river (G × 11)

The *Gammarus* spp. living in the Hudson River estuary constitute important food in the diet of many species of fish inhabiting the estuary. On the other hand, *Gammarus* eat bacteria, phytoplankton, other zooplankton, and also practice cannibalism.

The average life span of *Gammarus* in the Hudson River estuary is believed to be less than one year, because most of the adult population is consumed by other animals before growing old. However, 15 months is an acceptable upper limit for the lifetime of *Gammarus* in the Hudson River.

A magnified photograph (G × 11) of a typical *Gammarus* of the Hudson River estuary is shown below. The total average weight of a mixture of adult and young adult organisms was found to be [5.2 ± 1.5 [2]] mg wet by weighing 77 organisms. The average percentage of water in 70 organisms was (70 ± 6) p. cent. The distribution of mass throughout the

[1] 1σ due to propagation of errors associated with statistical counting only.
[2] 1σ.

body has been determined and it is given in Table V. Soft-tissue plus water comprise (74 ± 8) p. cent, exoskeleton (20 ± 5) p. cent, and the appendages only (6 ± 3) p. cent.

A detailed morphological description of the genus *Gammarus* is presented elsewhere [14].

RESULTS AND DISCUSSION

The alpha dose rates from radium to the whole body and distinct sites of *Gammarus* of Hudson River were calculated based on counting alpha tracks in autoradiographs [15]. The alpha dose rates for the whole body, G.I. tract, soft tissue, and a non-identified organ have been calculated on the basis of uniform distribution of ^{226}Ra. The range of a 5.64 MeV alpha particle in tissue-like media is about 40 μm, which is shorter than the diameters of the organs considered, and corresponds to about 3 p. cent the average diameter of *Gammarus* [6]. Accordingly, it is assumed that the mean alpha energy available for deposition per disintegration of ^{226}Ra (or ^{210}Po,

TABLE V

WEIGHT DISTRIBUTION IN *Gammarus*

Part of Organisms	Percentage
Soft tissue and water (^{a}).......	74 ± 8 (^{b})
Exoskeleton....................	20 ± (^{c})
Appendages (^{c})...............	6 ± 3

(^{a}) The water percentage of total weight in 70 organisms was (70 ± 6%) with 1 σ.

(^{b}) Indicates the approximate range for 10 organisms.

(^{c}) Including Telson

or ^{228}Th plus daughters, as the case may be) is totally absorbed in the media. The alpha dose rate is then expressed as follows:

$$\overline{D}_\alpha = 25{,}7\,\overline{C}, \tag{5}$$

where $\overline{D}_\alpha$ is in μrad/hr.; and $\overline{C}$ is the average concentration of ^{226}Ra (in pCi^{226} Ra/g) in the whole body or a particular organ of *Gammarus*.

Only 32 p. cent of the energy of alpha particles emitted from the atoms of ^{226}Ra plus daughters deposited in the exoskeleton of *Gammarus* will be delivered to the border layer internally adjacent to the *Gammarus* surface [15]. Thus, the average alpha dose rate to the exoskeleton can be expressed as

$$\overline{D}_\alpha = 25.7\,(0.32)\,\overline{C},$$

$$= 8.2\,\overline{C}. \tag{6}$$

The percentage of alpha energy emitted that is retained in the appendage is 48 p. cent [15]. Thus, the average alpha dose rate to the exoskeleton can be expressed by:

$$\overline{D}_\alpha = 25.7(0.48)\,\overline{C},$$
$$= 12.3\,\overline{C}. \tag{7}$$

The average concentrations of alpha emitters in different sites of *Gammarus* of the Hudson River, where a quasi-steady state situation is assumed to prevail, were estimated based on short term studies on the accumulation of ^{226}Ra plus daughters in *Gammarus* under laboratory conditions [14]. Thus this restriction must be kept in mind when using the values for the alpha dose rate for distinct sites of *Gammarus*.

Table I shows the average concentrations of ^{226}Ra in the whole body and distinct sites of *Gammarus* of Hudson River, as well as the average concentrations of ^{210}Po and ^{228}Th plus daughters, and the corresponding alpha dose rates. The alpha dose rate to the G.I. tract from ^{226}Ra plus daughters, excluding ^{210}Po, is 13 μrad/h (i. e., ~ 0.11 rad/yr). This dose rate is about 4 times higher than the alpha dose rate to the whole body due to ^{226}Ra plus daughters and ^{228}Th plus daughters (*see* Table I). Nevertheless, that alpha dose rate to the G.I. tract is only about half the annual external dose received by *Gammarus* from ^{40}K in sediments, as it can be seen in Table VIII. The G.I. tract should be considered as the "critical" organ for *Gammarus* because: (i) alpha emitters from the thorium series may contribute as high as twice that contribution from ^{226}Ra plus daughters to the alpha dose rate to the G.I. tract when both ^{228}Th and ^{226}Ra are found to have similar activity concentrations; and (ii) the dose equivalent (in terms of mrem/yr) has an enhancing quality factor for alpha particles, while ^{40}K (which contributes significantly to the external dose rate according to Table VIII, because of its presence in the sediments), is only a beta-gamma emitter. However, the concentration of ^{228}Th in the G.I. tract of *Gammarus* is still to be determined, although ^{228}Th is an important potential contributor to local alpha dose rates.

Hot spots of alpha emitters in soft tissue and exoskeleton may receive alpha dose rates 18 times higher than the average dose rates to soft tissues. However, those hot spots are believed to change sites within the organism as a function of time, thus the localized dose rates to hot spots may be meaningless, unless the average dose rate throughout the path of these hot spots can also be estimated.

The contents of ^{226}Ra, ^{228}Ra, ^{228}Th, ^{40}K and selected man-made radionuclides in *Gammarus* of Hudson River are listed in Table II, with the corresponding upper limits for beta dose rates. These upper limits were calculated by using LOEVINGER's approach [11] and including contributions from Auger – and conversion – electrons whenever those emissions might contribute significantly to the total beta dose rate. The conversion electrons from manmade ^{137}Cs contribute over 20 p. cent to the beta dose per pCi ^{137}Cs/g wet, while the Auger – plus conversion – electrons from the natural series emitters have contributions to the beta dose rate per pCi/g wet

approximately as follows (*see* Table II): 12 p. cent (from ^{228}Ra-^{228}Ac); 12 p. cent (from ^{228}Th plus daughters); and 9 p. cent (from ^{226}Ra-^{214}Po). The upper limits of the internal beta dose rates from man-made radionuclides to *Gammarus* of Hudson River near Indian Point is only 3.2 p. cent of the internal beta dose rates from natural radionuclides.

The contribution from internal gamma radiation to the total dose rate may be regarded as negligible, because it would be about 3 orders of magnitude lower than other component contributions to the total dose rate to *Gammarus*. The internal gamma – dose rate to zooplankton has been approached by WOODHEAD through the following equation developed by LOEVINGER *et al.*, [11, p. 853]:

$$\bar{D}_\gamma = \Gamma C \rho_0 \bar{g} \times 10^{-3} \mu \, rad/h \tag{8}$$

where: Γ, is the specific gamma – ray constant in cm^2. rad/h. mCi; C, is the activity concentration in pCi/g; ρ_0, is the density of the organism in g/cm^3; and $\bar{g}$ is the mean geometrical factor in centimeters.

Formulas for Γ and $\bar{g}$ have been first derived by MARINELLI *et al.* [12]. Values for Γ at several gamma energies are tabulated by LOEVINGER *et al.* [11, p. 889 and 904]. Thus the internal gamma dose rates to *Gammarus* can be easily calculated by placing $\bar{g} = 0.86$ cm [14, appendix III] for *Gammarus*, but it is not included in Table II, because the values are too low as compared to the beta dose rates.

Table VI shows the average concentrations of natural and selected man-made radionuclides in sediments of Hudson River at Indian Point in the biennium 1969-1970 and in the years 1972 and 1973. The average concentrations of selected man-made radionuclides shown in Table VI are calculated from measurements of samples taken from the section of Hudson River in front of Indian Point Nuclear Power Plants, thus representing averages calculated only with the maximum values of concentrations of man-made radionuclides in sediments. Potassium 40 itself presents specific activity in the sediments more than twice the sum of specific activities of all other gamma emitting radionuclides listed in Table VI.

In order to calculate the dose rate received by *Gammarus* from radionuclides in the sediments of Hudson River in front of Indian Point, the following assumptions have been made:

(i) radionuclides are uniformly distributed in an infinite slab of sediment;

(ii) ^{238}U is in equilibrium with daughters in sediment of Hudson River;

(iii) ^{232}Th is also in equilibrium with daughters in sediment of Hudson River;

(iv) *Gammarus* spend half day at sediment surface;

(v) the contribution of natural gamma emitters in the sediments to the exposure rate at 1 meter above sediment surface is about 1/2 of that contribution at sediment surface.

These assumptions were incorporated into the approximate expression presented by LENTSCH to calculate external dose rates at sediment surface [10].

TABLE VI

Average Concentations of natural and Selected manmade radionuclides
in sediments of Hudson River in front of Indian Point

Radionuclide	pCi dry		
	(53) [a] 1969-1970 [b]	(6) 1972 [c]	(19) 1973 [d]
^{40}K..........	18 ± 2	19 ± 2	17 ± 2
^{226}Ra........	0.91 ± 0.07	–	–
^{232}Th........	1.20 ± 0.1		–
^{137}Cs........	2.1 ± 1.9	2.7 ± 1.9	3.3 ± 1.8
^{134}Cs........	0.9 ± 1.4	3.9 ± 3.7	1.1 ± 0.8
^{54}Mn........	0.58 ± 0.58	2.5 ± 3.1	0.21 ± 0.18
^{60}Co..........	0.52 ± 0.51	1.3 ± 1.0	0.48 ± 0.47
^{58}Co..........	0.06 ± 0.32	0.13 ± 0.34	–
^{95}Zr-Nb.......	0.32 ± 0.63	–	–
^{144}Ce........	0.55 ± 0.52	–	–

[a] Parentheses indicate the number of samples. [b] Data taken from [10].
[c] Data taken from [22]. [d] Data taken from [23].

Accordingly, the contribution to the external dose rate due to beta and gamma emitters at sediment surface is given by the following expression:

$$\bar{D}_{ss}/\bar{C}_s = 4.67\,(\bar{E}_\beta + \bar{E}_\gamma) \tag{9}$$

where $\bar{D}_{ss}$ = average dose rate at sediment surface, mrad/yr; C_s = average concentration of radionuclide in the sediment, pCi/g dry, $\bar{E}_\beta$ = average beta energy, MeV/dis, and $\bar{E}_\gamma$ = average gamma energy, MeV/dis.

Equation (9) associated with the decay characteristics presented in [13] has been used to calculate the contributions per pCi/g dry of natural and selected man-made radionuclides found in sediments to the external dose rate to *Gammarus* at sediment surface and at 1 m above the sediment surface. Table VII presents the value of these contributions.

Using data from Tables VI and VII, the annual dose rates to *Gammarus* of Hudson River living in the vicinity of Indian Point have been evaluated for periods of time to which the average concentrations of radionuclides in sediments were available. The results of such evaluations are shown in Table VIII. From Table VIII it can be seen that in the biennium 1969-1970 the average annual external dose to *Gammarus* from man-made radionuclides was about 50 p. cent of the external dose from natural emitters in the sediments.

TABLE VII

CONTRIBUTION OF NATURAL AND SELECTED MAN-MADE RADIONUCLIDES
TO THE EXTERNAL DOSE RATE TO GAMMARUS ASSUMING AN INFINITE SLAB
OF SEDIMENT CONTAINING UNIFORMLY DISTRIBUTED RADIONUCLIDES [a]

Radionuclide	(mrad/yr)/(pCi/g dry)		At 1 m Above sediment surface
	At sediment surface		
	γ	β and γ	γ
^{40}K	3.7	13	1.9 [b]
^{238}U + Daughters........	23	66	12 [b]
^{232}Th + Daughters........	44	70	22 [b]
^{137}Cs..................	13	18	8.3
^{134}Cs..................	37	41	21
^{54}Mn..................	20	20	11
^{60}Co..................	58	60	33
^{58}Co..................	23	24	11
^{95}Zr-Nb..............	56	61	33
^{144}Ce + Daughters......	0.92	26	0.70

[a] Values based on LENTSCH [10] assuming that Gammarus spend half day at sediment surface and half day at 1 m above the sediment surface.

[b] Assuming half of the contribution at sediment surface.

Assuming that the external annual dose rates to *Gammarus* from the natural series for the years 1972 and 1973 remained the same as they were in the biennium 1969-1970, it may be observed that the annual external dose rate from man-made sources in the sediments in 1972 was about the same as the external dose rate from natural sources, while in 1973 the dose rate dropped again to the 1969-1970 level. These results are in agreement with the earlier estimated dose to benthos in the vicinity of Indian Point made by WRENN *et al.* [24].

The total dose rates to *Gammarus* of Hudson River near Indian Point from natural and selected man-made sources are presented in Table IX, under the assumption that the external dose rates for the biennium 1969-1970 represent the ordinary levels in the Hudson River in front of Indian Point. The values of internal alpha and beta dose rates have been taken from Tables I and II, respectively.

TABLE VIII

AVERAGE EXTERNAL DOSE RATE TO GAMMARUS DUE TO RADIONUCLIDES IN THE SEDIMENT OF HUDSON RIVER NEAR INDIAN POINT [a]

(mrad/yr)

Radionuclide	At sediment surface (1/2 day)						At 1 m above sediment (1/2 day)			$\beta + \gamma$ at sediment surface $+ \gamma$ at 1 m		
	1969-1970		1972		1973		1969-1970	1972	1973	1969-1970	1972	1973
	γ	$\beta + \gamma$	γ	$\beta + \gamma$	γ	$\beta + \gamma$	γ	γ	γ			
^{40}K	67	234	70	247	63	221	34	36	32	268	283	253
^{238}U + Daughters [b]	21	60	–	–	–	–	11	–	–	71	–	–
^{232}Th + Daughters [c]	53	84	–	–	–	–	26	–	–	110	–	–
^{137}Cs	27	38	35	49	43	59	17	22	27	55	71	86
^{134}Cs	33	37	144	160	41	45	19	82	23	56	242	68
^{54}Mn	12	12	50	50	4.2	4.2	6.4	28	2.3	18	78	7
^{60}Co	30	31	75	78	28	29	17	43	16	48	121	45
^{58}Co	1.4	1.4	3.0	3.1	–	–	0.66	1.4	–	2.1	4.5	–
^{95}Zr-Nb	18	20	–	–	–	–	11	–	–	31	–	–
^{144}Co + Daughters	0.51	14	–	–	–	–	0.39	–	–	14	–	–

(1969-1970 column sums indicated: 449 and 224)

[a] Obtained by multiplying the correspondint values of Tables VI and VII.

[b] Assuming equilibrium of ^{238}U and ^{226}Ra in the sediments and disregarding ^{222}Rn diffusion.

[c] Assuming equilibrium of ^{232}Th and ^{228}Ra in the sediments and disregarding ^{220}Rn diffusion.

TABLE IX

DOSE RATES TO GAMMARUS OF HUDSON RIVER NEAR INDIAN POINT
FROM NATURAL AND SELECTED MAN-MADE SOURCES OF RADIATION

Source of Radiation	(mrad/yr)		
	Natural	Man-made	Natural plus Man-made
Internal alpha.................	27	–	27
Internal beta (ᵃ)...............	6.2	0.2	6.4
External.....................	449	224	673
Cosmic radiation.............	10 (ᵇ)	–	10
TOTAL...................	492	224	716

(ᵃ) Upper limits assuming total absorption of beta radiation within *Gammarus*.

(ᵇ) Assuming constant exposure at a depth ($\sim$ 10 m) corresponding to $1/e$ of the dose rate of 28 mrad/yr at sea level [4, p. 194].

The dose rate due to cosmic radiation has been estimated, assuming a value corresponding to $1/e$ of the dose rate at sea level [4, p. 194]. The dose rate from radionuclides in water has been neglected because the concentrations of both natural and man-made radionuclides in water are at least 2 orders of magnitude lower than those concentrations in *Gammarus*.

CONCLUSIONS

The total external dose rate of 673 mrad/yr (449 mrad/yr from natural sources) received by *Gammarus* from radionuclides in the sediments of Hudson River is in general agreement with the dose estimations made earlier by FOLSOM and HARLEY [5], who put between 40 and 620 mrad/yr the dose rate from deep sea sediments when ^{40}K is the only contributor. The combined radiations of natural and man-made radionuclides in sediments cause 95 p. cent of the total (internal plus external) radiation dose rate received by *Gammarus* of Hudson River in front of Indian Point.

The inescapable conclusion inferred from Table IX is that low level radioactivity releases from a long time operating nuclear power station located at Indian Point do not increase significantly the dose rate received by *Gammarus* from natural sources and from radionuclides produced in weapon-tests. It appears safe to suppose, to a first approximation, that benthic organisms are subject to higher dose rates from both natural and man-made sources deposited in the sediments than other marine organisms.

The alpha dose rate from radium to the G.I. tract of *Gammarus* may be 1 to 2 orders of magnitude higher than the natural alpha dose rate to the whole body. Therefore, the G.I. tract should be considered the "critical organ" for *Gammarus*, and further studies should be undertaken to determine the dose to the G.I. tract of zooplankton from man-made alpha emitters.

The dose rate from internal alpha emitters to the whole body contributes with only 4 p. cent to the total dose rate received by *Gammarus* of the Hudson River at Indian Point. However, in terms of dose equivalent, the natural sources (internal plus external) would contribute with more than 75 p. cent of the total dose to *Gammarus*, because of the biological effects of high LET radiation that make the dose from internally emitted alpha particles at least as important as those from background gamma plus beta radiation.

Further studies on the dosimetry of marine organisms of the first two trophic levels should be encouraged because the amount of data available is meager, but there are in the literature conflicting ideas on radioresistance of marine organisms [2,17].

ACKNOWLEDGEMENT

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