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ABSTRACT. Comparison between the natural and man-made alpha radiation dose rates to plankton can be important for predicting the potential long-term effects on aquatic biota resulting from the routine or accidental radioactive releases from the nuclear fuel cycle. A contribution is made here towards the goal of comparing natural with man-made alpha radiation dose rates to plankton using the same method of calculation in both cases.

RESUMO. A comparação entre as taxas de dose de radiação para plancton devido a emissores alfa naturais e artificiais pode ser importante para prever os efeitos potenciais, a longo prazo, para a biota aquática resultantes das liberações radioativas, rotineiras ou acidentais, provenientes do ciclo de combustível nuclear. Este trabalho constitui uma contribuição no sentido de permitir uma comparação das taxas de dose de radiação alfa natural e artificial para plancton utilizando o mesmo método de cálculo nos dois casos.

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1. INTRODUCTION

It has been well known for many years that plankton play an important role in the biogenic migration of elements in the aquatic environment. However, only few attempts [1-8] have been made so far to estimate the radiation dose to plankton. Throughout time plankton have been exposed to several sources of natural radioactivily, including radionuclides of terrestrial origin, such as ^{40}K, ^{87}Rb and members of the ^{238}U and ^{232}Th series as well as radionuclides originating from cosmic rays, such as ^{3}H, ^{7}Be, ^{14}C, ^{32}P, ^{33}P and ^{35}S. Most of these radionuclides have an activity concentration in oceans higher than 3.7×10^{-4} Bq/ltr according to data available in the literature [9-11]. Knowledge of the effects associated with the biological accumulation and retention of natural radionuclides present in the aquatic environment can be useful for studying the long-range effects of man-made radionuclides with long half-lives which are incorporated into marine ecosystems. In particular and as is also well known, plankton concentrate some radionuclides 10 to 10^5 times their own concentrations in water.

Templeton et al. [12] suggested in 1971 that further studies were required on the concentrations of naturally occurring radionuclides and natural

background radiation doses in the environment as a basis for studies of the effects of radiation. Along the same lines Bowen et al. 13 stated that: "Lower trophic levels of the seas are likely to have greater concentrations of radioactivity than higher trophic levels. If the population explosion forces man to use these lower trophic levels as food sources, then the capacity of the seas to safely accept waste radioactivity will decrease". More recently, the International Atomic Energy Agency [14,15] called attention to the fact that the dosimetric models to aquatic biota need improvement. Accordingly, it is appropriate to emphasize here that a comparison between the natural alpha radiation dose to plankton and the alpha radiation doses received by these organisms from man-made produced radionuclides can be of paramount importance in the prediction and knowledge of the potential effects on aquatic biota resulting from routine or accidental releases of alpha emitters from the nuclear fuel cycles.

The objective here is to contribute towards the goal of comparing the upper limits of internal alpha radiation dose rates to plankton from natural and man-made radionuclides. The estimates are based upon data available on the plankton contents of alpha emitters, by using in both cases the same method of dosimetric calculation [7].

2. NATURAL RADIOACTIVITY IN PLANKTON

2.1. Capacity to accumulate natural radionuclides.

The capacity of plankton to concentrate natural radionuclides has been well recognized. Data on the content of natural radionuclides in organisms are summarized in the following sub-sections and in a series of three tables.

2.1.1. Natural Ra-226 in plankton.

Table I presents the data on the ^{226}Ra content of plankton, assuming for the purpose of comparison that the weight reduction factors are 2% ash/wet and 20% dry/wet. From these assumptions, the ^{226}Ra content in mixed plankton ranges from 2.0×10^{-15} g/g wet (i.e., ~ 7.3×10^{-5} Bq/g wet) in *Calanus finmarcus* [16] up to 7.6×10^{-13} g/g wet (i.e., ~ 2.8×10^{-2} Bq/g wet) in unspecified mixed plankton [24]. The average concentration of ^{226}Ra in phytoplankton goes up to 1.5×10^{-12} g/g wet (i.e., 5.6×10^{-2} Bq/g wet) reported by Shannon and Cherry [3] in *Chaetoceros* and *Rhizosolenia* from the Agulhas Current, South Africa. A plankton sample collected in the Hudson River, near Indian Point, United States of America and containing in the order of 10^4 *Gammarus* organisms, had a ^{226}Ra concentration of 4.8×10^{-14} g/g wet (i.e., ~ 1.7×10^{-3} Bq/g wet), which is within the range of the average concentrations for plankton from several origins, as can be seen in Table I.

2.1.2. Radium daughter activities in plankton.

The beta emitter ^{210}Pb and its alpha-emitter granddaughter ^{210}Po are both known to accumulate in plankton independently of the ^{226}Ra content of the organisms. Data on the ^{210}Pb and ^{210}Po contents of plankton appear in Table II. The concentrations of ^{210}Po in plankton range from 1.3×10^{-3} Bq/g wet [8] up to 2.2×10^{-1} Bq/g wet [26]. Data reported by Shannon et al. [30], Schell et al. [33], and Beasley et al. [34] indicate that ^{210}Po can accumulate in plankton independently of its long-lived grandparent ^{210}Pb.

2.1.3. Natural radioactive content in plankton.

Table III summarizes the data on ^{238}U, ^{235}U, ^{234}U, ^{232}Th, ^{230}Th, ^{228}Th and ^{228}Ra in plankton as found in the literature. The *Fucus* from the Swedish south west coast [35] have activity levels from 9.0×10^{-5} Bq ^{232}Th/g dry up to 4.0×10^{-2} Bq ^{230}Th/g dry.

The only reports of ^{238}U in the lower trophic levels are those by Kharkar et al. [26] and by Holm et al. [35], which indicate concentrations from 7.0×10^{-3} Bq/g dry in *Calanoids* and *Cyclopoids* [26] to 1.1×10^{-2} Bq/g dry in *Fucus* [35].

Data on the ^{238}U, ^{235}U, ^{232}Th and ^{230}Th contents of the IAEA seaweed reference sample as reported by Holm and Fukai [37] are also included in Table III for comparison purposes.

2.1.4. Biological removal of radium and thorium.

To the best of our knowledge, there is no report to date of direct measurements of the ^{228}Ra concentration in plankton. Kharkar et al. [26] estimated the ^{228}Ra concentration in *Calanoids* and *Cyclopoids* of the Caribbean Sea based upon the $^{228}Ra/^{226}Ra$ activity ratio in the Caribbean waters and from the ^{226}Ra concentration in these organisms, and Paschoa et al. [8] reported the ^{228}Ra content of *Gammarus* from the analysis of the ^{228}Ac photopeaks in gamma spectra of ashed samples of these organisms.

The quantitative biological removal of radium and thorium isotopes from water is still a question that has not been answered to the satisfaction of those interested in the problem of the disequilibrium of the thorium series in sea water. In particular, the distinction between the concentration of ^{228}Ra and ^{228}Th in plankton is important as it is not known whether the ^{228}Th content of plankton is only the result of the decay of ^{228}Ra within the organism or if it is also due to the direct uptake of ^{228}Th. Recently, Holm et al [27] observed that the life spans of the algae *Fucus visiculosus* and *Fucus serratus*, which grow in the waters of the Swedish south west coast, were not "long enough to explain the high concentration factor for ^{228}Th by in vivo build up from ^{228}Ra", and suggested that ^{228}Th might be "brought into a more bioavailable form through the decay of the ^{228}Ra". The conjugation of the gamma spectrometric analysis with alpha spectrometry may allow the ^{232}Th, ^{228}Ra and ^{228}Th contents of plankton to be distinguished. Further

research is expected in this direction. Investigators from South Africa claim that the biological removal of ^{228}Th from sea water and marine plankton would compete with the decay of ^{228}Ra as a source of ^{228}Th in plankton [36, 38]. However, as only alpha measurements were reported by the South African investigators [36,38], the actual ^{228}Ra content in plankton could not have been known. The uptake of ^{228}Ra by plankton would bring into existence, through beta decay, a source of the alpha emitter ^{228}Th within plankton that would be independent of the direct uptake of ^{228}Th by the organisms, making the internal alpha dosimetry for ^{228}Th more complicated. Cherry et al. [36] stated correctly that "... data on both ^{232}Th and ^{228}Th in both sea water and plankton will be required before the relative importance of biological removal of thorium isotopes can be assessed quantitatively". To this statement should be added that the direct determination of ^{228}Ra in plankton is also needed, since the concentration and the distribution of ^{228}Ra in waters of the world oceans have been reported [39 , 40], and the activity ratio of $^{228}Th/^{228}Ra$ ranges from 0.3 to 3.0 [40], regardless of the importance that the position and depth of sample collection might have in the overall problem of the disequilibrium of the thorium series in the world's ocean waters. On the other hand, Broecker et al. [41] reported that the activity ratio of $^{228}Th/^{228}Ra$ in open ocean waters averages 0.21, and suggested that the cause for this low ratio would be the high reactivity of thorium in surface water. Although this suggestion is supported by a number of facts, the possibility of a high uptake of ^{228}Ra by

plankton and other marine organisms from the water has not been fully explored as an explanation for the disequilibrium of the thorium series in sea water.

2.1.5. Natural K-40 in plankton.

The long-lived naturally occurring beta emitter ^{40}K has been reported to concentrate in plankton as follows: 1.8×10^{-2} Bq/g wet in *Gammarus* [8]; 1.8×10^{-1} Bq/g dry in *Euphausiid* [42]; and 4.0×10^{-1} Bq/g dry in *Copepod* [42]. However, the internal doses to plankton from ^{40}K can be considered negligible when compared with the natural internal alpha dose rates, as has been shown by Paschoa et al. [8] for *Gammarus*.

2.1.6. Total alpha-activity in plankton.

Total alpha activity in plankton is reported to have a maximum of 3.5 Bq/g dry [2], but data on total alpha activity will not be considered in the dosimetric estimates because of uncertainties in the alpha particle energies.

3. MAN-MADE ALPHA EMITTERS IN PLANKTON

Data on the contents of man-made alpha emitters in plankton have been collected for more than a decade. However, specific internal alpha dose estimates from man-made alpha emitters to plankton have been actually attempted by only few investigators so far [5-7].

Table IV summarizes the data available in the

literature on the contents of man-made alpha emitters in plankton. Paschoa and Baptista [7] reviewed the data on the ^{239}Pu content of plankton up to 1977. Such data are not included in Table IV.

Assuming the same weight reduction factors used in Table I (i.e., 20% dry/wet) the very limited data available in the literature show that the ranges of reported contents of the man-made alpha emitters plutonium and americium in plankton are normalized as Bq/g wet as follows: ^{238}Pu, 2.8×10^{-2} [37] to 3.7×10^{-2} [45] Bq/g wet; $^{239+240}Pu$, 3.8×10^{-5} [35] to 1.3 [46] Bq/g wet; ^{241}Am, 1.1×10^{-5} [35] to 4.6×10^{-1} [45] Bq/g wet. The normalized values as Bq/g wet for curium are the following: ^{242}Cm, 1.9×10^{-2} [45] Bq/g wet, ^{244}Cm, 2.2×10^{-4} [3] Bq/g wet.

4. INTERNAL DOSE RATES FROM ALPHA EMITTERS TO PLANKTON.

4.1. Existing data.

The radionuclides from the nuclear fuel cycle expected to enter the aquatic environment may include technologically enhanced concentrations of natural alpha emitters in the pre-reactor phase and transuranic alpha emitters in the post-reactor phase of the cycle. Therefore, estimations of the natural and man-made internal alpha dose rates to plankton from the data available can be helpful for comparing information which will allow a better assessment of the implications of the release of radionuclides from the nuclear fuel cycle to the aquatic environment. Preston [47] has already made some comparisons which indicated ratios for plankton dose rates at the orders of 10 for

fallout/natural background, and 10^3 for waste disposal at Windscale/natural background. Comparisons made specifically between internal dose rates from man-made and natural alpha emitters can be found also in references [5] and [7].

4.2. Methods of calculation

The methods of calculation used here for the purposes of comparing dose rates are the same conventional ones used by Paschoa and Baptista [7] to estimate the upper limits for alpha dose rates to the total body of plankton, assuming uniform distribution of the alpha emitters throughout the body, constant concentration and complete absorption of the mean alpha energy. Table V shows the ranges of the internal alpha dose rates estimated from data listed in Tables I-IV and Table 2 of reference [7], by using the conventional methodology mentioned above.

4.3. Internal alpha dose rates to plankton.

As it can be seen in Table V and Figure 1, the internal dose rates from naturally occurring alpha emitters range from 1.5 pGy/h from ^{232}Th in *Fucus* of the Swedish west coast to 1.6×10^{-1} µGy/h from ^{226}Ra in phytoplankton from the Agulhas Current, South Africa; while for man-made alpha emitters the internal alpha dose rates range from 1.2 pGy/h from ^{241}Am in *Fucus* of the Swedish west coast to 1.4×10^{-1} µGy/h from ^{239}Pu in zooplankton from Thule, Greenland, a few

months after the occurrence of an accident with a military aircraft nearby. However, Aakrog [48] pointed out that the plutonium concentrations in aquatic organisms living near the area of the accident have decreased with time.

5. FINAL REMARKS AND CONCLUSIONS

The knowledge of the micro-distribution of alpha emitters inside plankton allows a better estimation of the alpha dose rates to different organs, as illustrated by Paschoa et al. [8] for ^{226}Ra in *Gammarus* of Hudson River. However, for the purpose of a general comparison a conventional dosimetric methodology used consistently for all estimates, as is the case here, allows an overall picture to be depicted of the internal alpha dose rates to which plankton have been submitted so far.

Tentative conclusions, in view of the data summarized in the preceding sections, can be drafted as follows:

(i) The limited data available on the concentrations of alpha emitters in plankton allowed a crude but helpful comparison between the alpha radiation dose rates to plankton from naturally occurring and from man-made alpha emitters, when the same methodology is used to estimate these dose rates

(ii) This comparison shows that the ranges of internal alpha dose rates estimated to be received by plankton from a number of origins and of different species from both natural and man-made alpha emitters are similar

(iii) Five orders of magnitude are covered by the range of estimated internal alpha dose rates, the two highest values being 1.6×10^{-1} μGy/h from ^{226}Ra in the phytoplankton *Chaetoceros* and *Rhizosolenia* from the Agulhas Current, South Africa, and 1.4×10^{-1} μGy/h from ^{239}Pu accumulated at one time in the zooplankton *Gammarus* from Thule, Greenland, due to an accidental release associated with military activities

(iv) The highest estimated internal alpha dose rate traceable directly to nuclear fuel cycle actitivies is 5.4×10^{-2} μGy/h from ^{241}Am in the seaweed *Porphyra* from the Cumbrian coast

(v) Further research should be developed in the direction of the knowledge of the internal distribution of the alpha doses to plankton of different species in order to allow realistic predictions of the potential effects on these organisms resulting from routine or accidental releases of alpha emitters from the nuclear fuel cycle.

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TABLE II. DATA ON ^{210}Po AND ^{210}Pb CONTENT IN PLANKTON

Genus and/or species	Origin	Bq/g wet				Ref.
		^{210}Po		^{210}Pb		
		phytoplankton*	zooplankton*	phytoplankton*	zooplankton*	
-	South Pacific	-	[n] 7.4×10^{-2}	-	-	[27]
-	Cape of Good Hope South Africa	[d] 1.0×10^{-1} (20)	[d] 1.7×10^{-1} (78)	-	-	[28]
Euphausia Pacifica	Oregon United States of America	-	-	-	[d] 4.1×10^{-3} (10)	[29]
-	Capetown, South Africa	3.9×10^{-3} (3)	1.5×10^{-2} (11)	1.2×10^{-3} (3)	1.2×10^{-3} (11)	[30]
-	South Africa	-	1.4×10^{-2}	-	1.1×10^{-3}	[31]
Dinoflagelates	California United States of America	$<3.3\times10^{-3}$	-	-	-	[32]
-	Lake Washington, Washington State United States of America	-	2.3×10^{-3} (3)	-	1.7×10^{-4} (3)	[33]
Copepod	Lake Washington, Washington State United States of America	-	1.3×10^{-3} (2)	-	2.4×10^{-4} (2)	[33]
Euphausiid	Juan de Fuca, Washington State United States of America	-	1.8×10^{-1} (9)	-	1.1×10^{-3} (9)	[33]
-	Oregon United States of America	-	8.8×10^{-3}	-	6.7×10^{-4}	[34]
Gammarus	Hudson River United States of America	-	1.3×10^{-3}	-	-	[8]
Calanoids and *Cyclopoids*	Caribbean Sea	-	[d] 1.1 (16)	-	7.0×10^{-2} (19)	[26]

n Not specified if ash, dry or wet weight.
d Concentration per dry weight.
* Figures inside parentheses indicate the number of samples used to calculate the average.

TABLE I. SUMMARY OF THE DATA ON ^{226}Ra CONTENT IN PLANKTON

Genus and/or species	Origin	× 10^{-12} g/g phytoplankton*	× 10^{-12} g/g zooplankton*§	Ref.
Calanus finmarcus	-	-	[a]0.1 (0.002)	[16]
Schizopood crustaceous	Mission Bay, California United States of America	-	[d]0.04 (0.008)	[17]
Diatom	-	[d]1 (0.2)	-	[18]
-	North Sea	-	(0.275)	[19]
-	-	-	[d]1.8 (0.4)	[20-22]
-	Providence Channel Bahamas	-	[†d]0.22||6||(0.04)	[23]
-	Lake Lower Bass Canada	-	[†d]0.92||18||(0.2)	[24]
-	Lake Upper Bass Canada	-	[†d]1.10||18||(0.2)	[24]
-	Lake Maskinorge Canada	-	[†d]3.8||18||(0.8)	[24]
Chaetoceros and Rhizosolenia	Agulhas Current South Africa	[††d]7.7 (1.5)	-	[3]
Sketotenema Nitzchia	West of South Africa	[d]1.0 (0.2)	-	[3]
-	South Africa	-	[††d]2.5||15||(0.5)	[3, 25]
Gammarus	Hudson River United States of America	-	(0.048)	[8]
Calanoids and Cyclopoids	Caribbean Sea	-	[d]0.13||19||(0.03)	[26]

a Concentration per ash weight.
d Concentration per dry weight.
* Figures inside parentheses indicate estimated concentration per wet weight.
§ Figures inside double vertical bars indicate the number of samples used to calculate the average.
† Not specified whether phytoplankton or zooplankton, but it is assumed to be mostly zooplankton.
†† Seven phytoplankton samples among fifteen plankton samples.

TABLE III. SUMMARY OF THE CONTENTS OF ^{238}U, ^{235}U, ^{234}U, ^{232}Th, ^{230}Th, ^{228}Th AND ^{226}Ra IN PLANKTON

Genus and/or species	Origin	Bq/g A_U*†	A*	A_{Th}*†	A*	^{228}Ra	Ref.
Calanoids and *Cyclopoids*[z]	Caribbean Sea	$^{d}7.0\times10^{-3}$ (5)	238	$^{d}1.1\times10^{-3}$(5)	232	$^{zd}1.9\times10^{-3}$	[26]
		-	-	$^{d}1.5\times10^{-3}$(4)	228	-	
Fucus vesiculosus and *Fucus serratus*[z,**]	Swedish south west coast	$^{d}1.11\times10^{-2}$	238	$^{d}9.0\times10^{-5}$	232	-	[35]
		$^{d}4.5\times10^{-4}$	235	$^{d}4.0\times10^{-2}$	230	-	
		$^{d}1.27\times10^{-2}$	234	$^{d}5.0\times10^{-3}$	228	-	
-	South Africa	-	-	$^{pw}1.0\times10^{-3}$ $^{zw}3.0\times10^{-4}$	228	-	[36]
		-	-	$^{z\dagger\dagger}1.4\times10^{-2}$ (15)	228	-	[25]
Gammarus[z]	Hudson River United States of America	-	-	$^{w}8.1\times10^{-4}$	228	$^{zw}2.3\times10^{-3}$	[8]
IAEA seaweed[§]	-	$^{d}8.5\times10^{-3}$	238	$^{d}3.0\times10^{-4}$	232	-	[37]
		$^{d}1.1\times10^{-3}$	235	$^{d}6.7\times10^{-3}$	230	-	
		$^{d}9.3\times10^{-3}$	234	-	234	-	

* A = Atomic mass.
** Brown algae.
† Figures inside parentheses indicate the number of samples used to calculate the average.
d Per gram dry.
w Per gram wet.
†† Not specified whether phytoplankton or zooplankton, but it is assumed to be mostly zooplankton.
§ Collected from the vicinity of a reprocessing plant.
p Phytoplankton.
z Zooplankton.

TABLE IV. SUMMARY OF THE CONTENTS OF MAN-MADE ALPHA EMITTERS* IN PLANKTON

Sample	Origin	Bq/g A_{Pu}§	A§	A_{Am}§	A§	A_{Cm}§	A§	Ref.
Algae, genus Rhizoclonium	Colorado United States of America	$^{d}3.5\times10^{-2}$	239	$^{d}4.3\times10^{-3}$	241	-	-	[43]
Mixed plankton	Lake Michigan United States of America	$^{w**}1.6\times10^{-4}$	239+240	$^{w}1.1\times10^{-2}$	241	-	-	[44]
Fucus	Swedish south west coast	$^{d}1.9\times10^{-4}$	239+240	$^{d}5.3\times10^{-5}$	241	-	-	[35]
Seaweed†	Cumbrian coast United Kingdom	$^{w}3.7\times10^{-2}$ $^{w}1.6\times10^{-1}$	238 239+240	$^{w}4.6\times10^{-1}$ -	241 -	$^{w}1.9\times10^{-2}$ -	242 -	[45]
IAEA seaweed††		$^{d}1.4\times10^{-1}$ $^{d}1.0$	238 239+240	$^{d}3.7\times10^{-1}$ -	241 -	$^{d}1.1\times10^{-3}$ -	244 -	[37]

§ A = Atomic mass.
* For further data on ^{238}Pu and ^{239}Pu up to 1977 see Ref. [7].
** Included also in Ref. [7].
d Per gram dry weight.
w Per gram wet weight.
† Highest concentrations.
†† Collected from the vicinity of a reprocessing plant.

TABLE V. DOSE FACTORS AND RANGE OF INTERNAL DOSE RATES FOR NATURAL AND MAN-MADE ALPHA EMITTERS IN PLANKTON

Nuclide	Dose factor (μGy/h)/(Bq/g)	Site	Dose rate (range) μGy/h from	to	Site	
^{210}Po	1.13×10^{-1}	Hudson River and Lake Washington United States of America	1.5×10^{-4}	2.5×10^{-2}	Caribbean Sea	Naturally occurring
^{226}Ra**	1.02×10^{-1}	Unknown	2.0×10^{-4}	1.6×10^{-1}	Agulhas Current South Africa	
^{228}Th†	1.15×10^{-1}	South Africa and Caribbean Sea	3.5×10^{-5}	3.2×10^{-4}	South Africa	
^{230}Th	1.00×10^{-1}	(IAEA seawwed)††	1.3×10^{-4}	8.0×10^{-4}	Swedish south west coast	
^{232}Th	8.52×10^{-2}	Swedish south west coast	1.5×10^{-6}	1.9×10^{-5}	Caribbean Sea	
^{234}U	1.02×10^{-1}	(IAEA seaweed)††	1.9×10^{-4}	2.6×10^{-4}	Swedish coast west coast	
^{235}U	8.95×10^{-2}	Swedish south west coast	8.1×10^{-6}	2.0×10^{-5}	(IAEA seaweed)††	
^{238}U	8.95×10^{-2}	Caribbean Sea	1.3×10^{-4}	2.0×10^{-4}	Swedish coast west coast	
^{238}Pu	1.17×10^{-1}	(IAEA seaweed)††	3.3×10^{-3}	4.3×10^{-3}	Cumbrian coast United Kingdom	Man-Made
^{239,240}Pu	1.11×10^{-1}	Swedish south west coast	4.2×10^{-6}	1.4×10^{-1}	Thule, Greenland	
^{241}Am	1.17×10^{-1}	Swedish south west coast	1.2×10^{-6}	5.4×10^{-2}	Cumbrian coast United Kingdom	
^{242}Cm	1.30×10^{-1}	-	-	2.5×10^{-3}	Cumbrian coast United Kingdom	
^{244}Cm	1.24×10^{-1}	-	-	2.8×10^{-5}	(IAEA seaweed)††	

* $Df = 2.13\times10^{2}\left[\frac{(dis/h)}{(Bq/g)}\frac{\mu Gy}{MeV}\right]\sum_i \bar{E}_{\alpha i}$ (MeV) where $\sum_i \bar{E}_{\alpha i}$ were taken from Ref. [7].

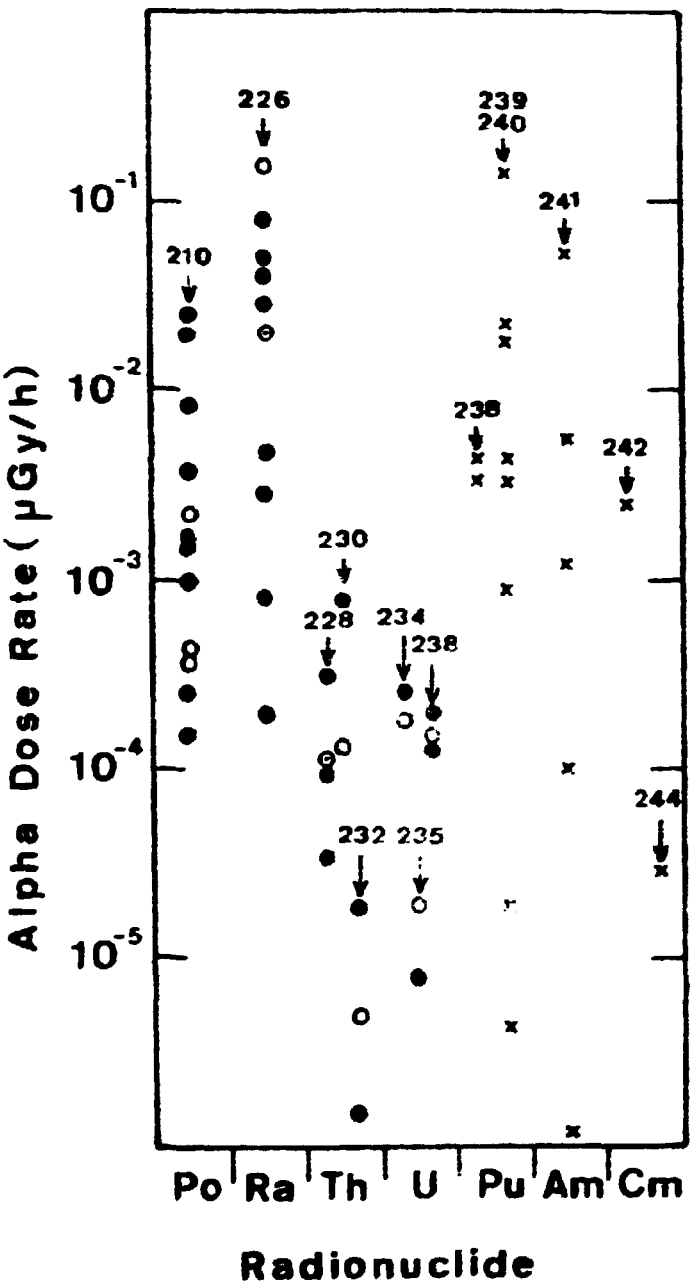
** Assuming total radon escape.

† Ignoring possible contributions from the endogeneous decay of ^{228}Ra.

†† Collected from the vicinity of a reprocessing plant.

Figure caption.

Fig. 1. Alpha internal dose rates to plankton: O phytoplankton, ● zooplankton, x not specified.


Alpha Dose Rate (μGy/h)
10^-1
10^-2
10^-3
10^-4
10^-5
210
226
230
228
234
238
232
235
239
240
241
238
242
244
Po
Ra
Th
U
Pu
Am
Cm
Radionuclide