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Effects of Arctic Temperatures on Distribution and Retention of the Nuclear Waste Radionuclides ^{241}Am, ^{57}Co, and ^{137}Cs in the Bioindicator Bivalve *Macoma balthica*

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ABSTRACT

The disposal of radioactive wastes in Arctic seas has made it important to understand the processes affecting the accumulation of radionuclides in food webs in coldwater ecosystems. We examined the effects of temperature on radionuclide assimilation and retention by the bioindicator bivalve Macoma balthica *using three representative nuclear waste components, ^{241}Am, ^{57}Co, and ^{137}Cs. Experiments were designed to determine the kinetics of processes that control uptake from food and water, as well as kinetic constants of loss. ^{137}Cs was not accumulated in soft tissue from water during short exposures, and was rapidly lost from shell with no thermal dependence. No effects of temperature on ^{57}Co assimilation or retention from food were observed. The only substantial effect of polar temperatures was that on the assimilation efficiency of ^{241}Am from food, where 10% was assimilated at 2°C and 26% at 12°C. For all three radionuclides, body distributions were correlated with source, with most radioactivity obtained from water found in the shell and food in the soft tissues. These results suggest that in general Arctic conditions had relatively small effects on the biological processes which influence the bioaccumulation of radioactive wastes, and bivalve concentration factors may not be appreciably different between polar and temperate waters.* © *1998 Elsevier Science Ltd. All rights reserved*

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INTRODUCTION

One of the fundamental processes influencing marine food web structure is the cycling of elements among trophic levels. These same biogeochemical pathways, although essential to the transfer and acquisition of nutrients by marine organisms, can also serve as routes for the biological accumulation of anthropogenic contaminants. Numerous studies have examined the trophic transfer of diverse contaminants in marine ecosystems (Luoma, 1983, 1989; Fisher and Reinfelder, 1995), and marine organisms such as bivalves have been extensively used as bioindicators of contaminant exposure (Phillips, 1977; Goldberg *et al.*, 1978).

In spite of the relatively large amount of work which has been done in these areas, there is surprisingly little information on the biological interactions of contaminants in ecosystems other than those in temperate waters. In particular, the potential for trophic transfer and bioaccumulation in coldwater ecosystems has been little investigated, even though it is evident that the lower metabolic rates of ectotherms and enhanced lipid deposits at colder temperatures could affect contaminant accumulation and retention. The recent disclosure of extensive disposals of nuclear wastes in the Russian Arctic (White Paper, 1993; Mount *et al.*, 1994) has underscored the need for realistic models of radioactive contaminant pathways in polar marine organisms (Fowler *et al.*, 1994; Hutchins *et al.*, 1996*a*,*b*).

We addressed this problem by examining the retention, as a function of temperature, of two radioisotopes (^{241}Am and ^{57}Co) in the clam *Macoma balthica*. The isotopes were obtained from both water and food. We also examined the retention of ^{137}Cs obtained from water. These radioisotopes represent the three main categories of radionuclides present in the dumped Russian waste. ^{241}Am is a transuranic component of the waste which can also be used as a model for other highly particle-reactive actinides and rare earth elements. ^{57}Co is intermediate in particle reactivity and can be used to model the behavior of the important activation product ^{60}Co. ^{137}Cs (along with ^{134}Cs) is an abundant fission product, and the least particle-reactive of the three elements. Of these elements, only Co is a biologically required element.

Macoma balthica and the closely related *M. calcarea* and *M. moesta* are common members of Arctic benthic communities (Miquel, in press). These clams can serve both as bioindicators of radionuclide exposure, and as conduits for the transfer of contaminants to higher trophic levels. Predators such as demersal fish and some marine mammals (e.g. walrus) feed on benthic bivalves, thus representing a potential source of radionuclide exposure to indigenous human populations in the Arctic.

Macoma balthica and other bivalves have been widely used as bioindicator species in temperate ecosystems (Luoma *et al.*, 1985; Cain and Luoma, 1990). Bioaccumulation and bioconcentration factors in indicator species are determined by the balance between influx rates and loss rates, both of which might be sensitive to temperature. In this study we used *M. balthica* to explore the possibility that temperature might affect radionuclide loss rates. Information on isotope interactions at realistic polar temperatures should allow more accurate modeling and estimation of the risks associated with nuclear waste disposals in polar seas, as well as the potential for bivalves such as *Macoma* to act as bioindicators of food chain accumulation in coldwater habitats in general.

MATERIALS AND METHODS

Macoma balthica individuals were obtained from intertidal mudflats in South San Francisco Bay, California and acclimated to experimental temperatures (2 or 12°C) and salinity (35‰) for several weeks, during which they were fed unlabeled diatom cultures (*Thalassiosira pseudonana*, clone 3H). Clams were blotted dry and live weights for each individual were determined before use in experiments. Because contaminant uptake and retention differ with body weight in this species (Strong and Luoma, 1981), we used medium-sized animals of relatively uniform weights (0.7–1.5 g).

Exposure to isotopes was examined from both food and dissolved (solute) phases. Uptake from solution, and depuration from both dissolved and food sources were monitored non-destructively with live animals using a large well NaI(Tl) gamma detector interfaced to a Canberra Series 35+ multichannel analyzer. Activities were standardized using geometrically appropriate standards, and counting times were adjusted to yield propagated counting errors of $< 5\%$. Gamma activities of isotopes were measured at 60 keV (^{241}Am), 122 keV (^{57}Co), and 662 keV (^{137}Cs) and were corrected for counting efficiencies, energy spillover between detection windows, and radioactive decay for ^{57}Co ($t_{1/2} = 272$ d). Isotope additions were as microliter quantities in 0.1 N HCl (^{57}Co, ^{137}Cs) or 3 N HNO_3 (^{241}Am), and were neutralized with appropriate quantities of Suprapur NaOH.

For food exposure experiments, cultures of the centric diatom *T. pseudonana* were grown in modified f/2 medium (no EDTA, Cu or Zn) at 16°C using a 14 h photoperiod under cool-white fluorescent lights (170 μEin m^{-1} s^{-1}). Log-phase cultures were harvested by gentle filtration and resuspended (10^5 cells ml^{-1}) in radiolabeling medium containing ^{241}Am (123 kBq l^{-1}), ^{57}Co (123 kBq l^{-1}) and ^{137}Cs (185 kBq l^{-1}). Uptake of the three isotopes by diatoms was followed using the methods described in Fisher *et al.* (1983).

For dissolved exposure experiments, six groups of 6–10 clams were exposed to radiolabeled water (^{241}Am, ^{57}Co, and ^{137}Cs added at the same concentrations as in the diatom labeling medium) for 12 h. The goal of the short exposures was to determine unidirectional influx of the radionuclides into the animals by measuring concentrations at the earliest point that significant uptake was detectable (Neame and Richards, 1972; Luoma, 1977). Measurements of influx kinetics by initial-rate transfer are based on the assumption that radionuclide concentrations in the animal at the time of sampling are small enough for outward transfer to be ignored. This assumption is typically reasonable for trace elements where turnover rates are relatively slow. Unidirectional influx from solution can be a critical kinetic parameter controlling net bioaccumulation (Wang *et al.*, 1996; Luoma and Fisher, 1997). Each group of clams was exposed at the appropriate temperature in 50 ml 0.2 μm-filtered seawater with aeration. The groups of animals were then transferred into unlabeled circulating seawater held in an aerated 20-l aquarium at the appropriate temperatures, and loss of all three isotopes was followed over a 6-week period. These experiments were designed to have negligible recycling of each radionuclide and thus determine rate constants describing loss (efflux). Water was changed every 2–3 days in the depuration containers to reduce isotope recycling, and the clams were fed unlabeled diatom cultures. Food exposure experiments used the same loss protocol following a 4 h feeding of radiolabeled diatoms. For the feeding experiments, six groups of six clams were fed in 100 ml 0.2 μm-filtered aerated seawater in the dark, with radiolabeled diatoms added at 7.7×10^6 cells ml^{-1}.

All activities are reported as the average of the six groups of clams (6–10 animals/group) in each treatment. For solute exposure experiments, results are presented as the percentage retained of the radioactivity present in the clams at the beginning of the depuration period (end of the exposure period). Loss from food exposure was expressed as the percentage of the remaining radioactivity in the animals directly after feeding. Loss rates of rapid and slowly exchanging pools were calculated by stripping loss curves according to methods described by Riggs (1963). Curve stripping and regression analysis were performed using JMP 3.1 software from SAS Institute, Inc. (Cary, NC, USA) and single factor analysis of variance was performed on all regression parameters. Assimilation efficiencies for isotopes obtained from food, and percentages of isotopes in slowly exchanging pools following dissolved exposure, were calculated by extrapolating the slope of the regression line in the slowly lost pools back to the y-intercept.

Individuals were removed at the initial ($n = 2$–3) and final ($n = 12$–26) time points of depuration from each experiment for detailed dissections to determine the body distributions of the isotopes. Dissections included measurements of gamma radioactivity in the shell, visceral mass, mantle, gills, adductor muscle, siphon, foot, and pallial fluid (collected by conducting dissections over absorbant tissue and counting the absorbed liquid).

RESULTS

Loss of radionuclides obtained from food

Because the diatoms radiolabeled for the food exposure experiments did not accumulate ^{137}Cs, measurements of *Macoma* retention of this isotope obtained from food sources

TABLE 1
Percent of Total Body Radioactivity of ^{57}Co and ^{241}Am (Obtained from Food and Dissolved Pathways at 2°C and 12°C) in Shell, Visceral Mass, and Pallial Fluid

Treatment	*Time*	*Shell*	*Visceral mass*	*Pallial fluid*
^{57}Co: 12°C food	Initial	8.3 ± 0.8	74.0 ± 53.2	14.2 ± 8.7
^{57}Co: 12°C food	Final	38.3 ± 13.0	18.8 ± 12.8	30.4 ± 34.1
^{57}Co: 2°C food	Initial	No data	No data	No data
^{57}Co: 2°C food	Final	No data	No data	No data
^{57}Co: 12°C water	Initial	89.2 ± 25.5	1.0 ± 0.6	7.4 ± 1.0
^{57}Co: 12°C water	Final	66.6 ± 25.4	7.9 ± 5.9	14.3 ± 4.6
^{57}Co: 2°C water	Initial	84.3 ± 55.6	1.5 ± 1.0	10.0 ± 4.0
^{57}Co: 2°C water	Final	92.2 ± 40.4	1.2 ± 0.6	5.3 ± 1.8
^{241}Am: 12°C food	Initial	2.4 ± 0.5	85.1 ± 61.5	10.3 ± 6.9
^{241}Am: 12°C food	Final	11.1 ± 4.4	77.7 ± 69.4	8.1 ± 11.1
^{241}Am: 2°C food	Initial	8.4 ± 4.6	44.7 ± 47.8	38.7 ± 24.6
^{241}Am: 2°C food	Final	10.1 ± 2.8	83.7 ± 57.5	4.6 ± 3.6
^{241}Am: 12°C water	Initial	89.4 ± 9.4	4.5 ± 6.2	4.9 ± 1.6
^{241}Am: 12°C water	Final	90.7 ± 15.6	4.9 ± 1.1	3.6 ± 1.3
^{241}Am: 2°C water	Initial	95.6 ± 22.8	0.3 ± 0.6	3.4 ± 0.8
^{241}Am: 2°C water	Final	83.6 ± 28.6	4.4 ± 7.7	4.4 ± 1.8

Data are presented for dissections at the Initial and Final timepoints of depuration; errors are the standard deviations of 2–3 (Initial) or 12–26 (Final) replicate dissections. Amounts of ^{137}Cs in all soft tissues, as well as amounts of ^{57}Co and ^{241}Am associated with mantle, gills, adductor muscle, siphon, and food were negligible for most samples.

were not possible. *Macoma* dissections after 4 h feeding on radiolabeled diatoms showed that both ^{241}Am and ^{57}Co were mainly (92–98%) in visceral mass and pallial fluid (Table 1), suggesting little recycling during the feeding period. At the end of the 6 week depuration period isotopes obtained from feeding were still mostly in soft tissues (62–90%), although some minor recycling may have occurred during the extended depuration, especially for Co. Although the fraction on the shell increased during the depuration period, depuration results after food exposure principally reflect loss rates from soft tissues. Amounts of ^{241}Am and ^{57}Co associated with body parts other than visceral mass and pallial fluid (including mantle, gills, siphon, adductor muscle and foot) were generally negligible.

At both temperatures, differences in depuration patterns between ^{241}Am and ^{57}Co obtained from food were evident. ^{241}Am exhibited a two-compartment loss, with a rapid period over the first 2–3 days, followed by much slower losses over the remaining 6 weeks of the experiment (Fig. 1A). A three-compartment system best fit the observed loss of ^{57}Co, with two slower pools following an initial rapid loss, one between about 2 and 10 days, and a much slower one from about 10 days to the end of the depuration period (Fig. 1B). The most rapid compartment resembled the initial loss of ^{241}Am, occurring over the first 2–3 days. For both of the isotopes this initial rapid loss is likely to be due to egestion of the labeled prey cells, as gut clearance is essentially complete in 72–96 h with this species (Decho and Luoma, 1991). The slowly exchanging fractions represented the assimilated isotope.

Assimilation efficiencies of ^{241}Am from food differed significantly between temperatures (Table 2). At 12°C, the AE was 26% (74% rapidly egested); at 2°C it was 10% (90% rapidly egested). Lower temperatures had no effect on the loss rates of assimilated ^{241}Am; the biological half-lives ($Tb_{1/2}$) of the slow compartments were 63 d at 12°C and 69 d at 2°C (Table 2).

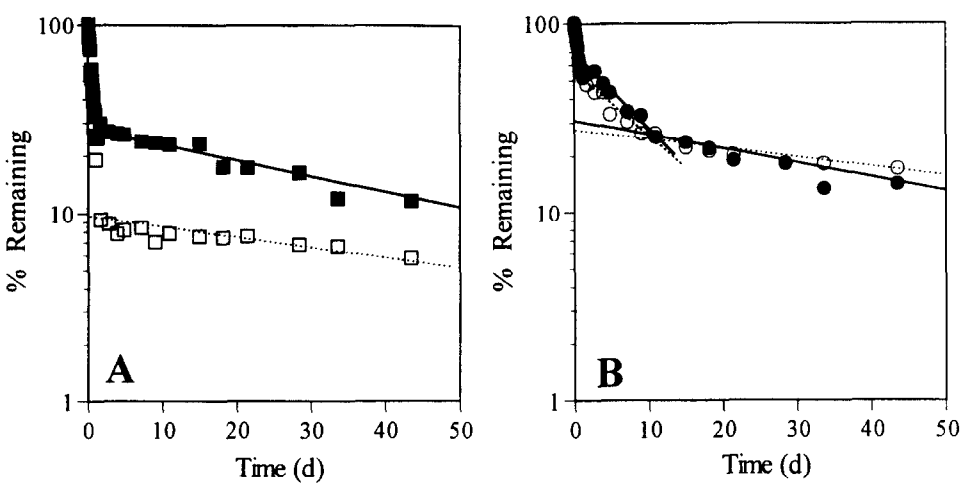

Fig. 1. Loss of ^{241}Am (A) and ^{57}Co (B) by *Macoma balthica* exposed through feeding on radiolabeled diatoms at 2°C (open symbols) and 12°C (closed symbols), expressed as the percent of the radioactivity remaining in the clams at the beginning of the depuration period. No exposure of ^{137}Cs from food was possible (see Results). Regression lines indicate the best fit for each of the radioisotope pools in the clams. For descriptions of pools, see Table 2.

TABLE 2
Rate Loss Constants (k) from ln-Transformed Data for All Loss Compartments for Each Isotope and Treatment

		CI			*CII*			*CIII*		
		$k\ (d^{-1})$	$Tb_{1/2}\ (d)$	*% in pool*	$k\ (d^{-1})$	$Tb_{1/2}\ (d)$	*% in pool*	$k\ (d^{-1})$	$Tb_{1/2}\ (d)$	*% in pool*
^{57}Co	12°C food	−0.50 ±0.3	1.4	18±6	−0.13 ±0.1	5.3	63±28	−0.02 ±0.005	35	30±12
	r^2	0.78 ±0.2			0.78 ±0.2			0.85 ±0.05		
	2°C food	−0.73 ±0.3	0.9	37±13	−0.12 ±0.03	5.8	35±7	−0.01 ±0.002	69	28±9
	r^2	0.96 ±0.07			0.77 ±0.1			0.70 ±0.2		
	12°C water	−0.14* ±0.02	5.0	21±3	−0.03 ±0.02	23	21±12	−0.005* ±0.002	139	58±10
	r^2	0.78 ±0.03			0.90 ±0.06			0.69 ±0.2		
	2°C water	−0.17* ±0.02	4.1	31±3	−0.02 ±0.007	35	7±3	−0.002* ±0.001	347	62±3
	r^2	0.68 ±0.06			0.88 ±0.07			0.69 ±0.1		
^{241}Am	12°C food	−0.87* ±0.25	0.8	74* ±6	−0.011±0.004	63	26* ±5			
	r^2	0.84 ±0.08			0.88 ±0.13					
	2°C food	−1.78* ±0.4	0.4	90* ±9	−0.01 ±0.003	69	10* ±9			
	r^2	0.97 ±0.01			0.90 ±0.1					
	12°C water	−0.17 ±0.05	4.1	19±4	−0.02 ±0.007	35	10±6	−0.007 ±0.003	99	71±4
	r^2	0.88 ±0.05			0.89 ±0.05			0.81 ±0.05		
	2°C water	−0.14 ±0.01	5.0	22±2	−0.02 ±0.005	35	12±4	−0.005 ±0.005	139	66±2
	r^2	0.81 ±0.04			0.92 ±0.03			0.97 ±0.03		
^{137}Cs	12°C water	−0.74 ±0.08	0.9	78* ±3	−0.11 ±0.03	6.3	11±4	−0.03 ±0.004	23	11±3
	r^2	0.70 ±0.05			0.92 ±0.05			0.95 ±0.02		
	2°C water	−0.72 ±0.07	1.0	67* ±3	−0.13 ±0.01	5.3	19±3	−0.036 ±0.007	19	14±3
	r^2	0.75 ±0.05			0.96 ±0.02			0.97 ±0.02		

CI is the most rapidly lost compartment and CIII is the most slowly lost. Also shown are biological half-lives ($Tb_{1/2}$), and percentages of the total original activity (time 0 of depuration) in each compartment, and r^2 values for each regression. Regression analyses were performed on data for individual clams; values presented are means ±1 SD of five or six replicate individuals.
*Denotes statistically significant effect of temperature ($P < 0.05$).

Assimilation efficiencies for ^{57}Co from food, if calculated as the amount in pool CIII, were indistinguishable between treatments; curve-stripping indicated that 30% was assimilated at 12°C and 28% at 2°C (Table 2). However, only 18% of the ^{57}Co was egested (in pool CI) at 12°C compared with 37% at 2°C (Table 2). Inspection of the data shows the similarity in the proportion of assimilated material at the two temperatures (Fig. 1B). Temperature did not affect the loss rate constant of ^{57}Co from the intermediate pool (CII): $-0.13\,d^{-1}$ at 12°C and $-0.12\,d^{-1}$ at 2°C (Table 2). The calculated rate loss constant from the slowest pool (CIII) was highly dependent on the specific data points chosen when stripping the curves, and calculated values were twice as high at 12°C as at 2°C (Table 2). However, inspection of the data indicated little difference in loss rates between the two temperatures (Fig. 1B).

Loss of radionuclides obtained from the dissolved phase

In these short exposure experiments, isotope distributions in tissues were strongly dependent on source. ^{241}Am and ^{57}Co accumulated by *M. balthica* from solution were primarily associated with the shells of the animals (Table 1). ^{137}Cs was entirely on the shell (not shown), with no detectable concentration in soft tissues. While depuration after food exposure reflected loss rates from tissues, depuration after dissolved exposure represented primarily loss from the shell. Loss of all three isotopes at both temperatures could be best described by a three-compartment model (Table 2). $Tb_{1/2}$s of the most rapidly lost pool (CI) of ^{57}Co were significantly different between the two temperatures, but differences were small ($-0.14\,d^{-1}$ at 12°C and $-0.17\,d^{-1}$ at 2°C); similarly loss rate constants were significantly greater (but with only small differences) in the slowest pool (CIII) (Table 2). Temperature had no effect on loss rates of ^{137}Cs and ^{241}Am from any pool, and loss rates of ^{241}Am and ^{57}Co were comparable for each pool (Table 2). Pool sizes did not differ significantly between temperatures for ^{57}Co or ^{241}Am, but the fraction in CI for ^{137}Cs was significantly (but only slightly) greater at 12°C than at 2°C (Table 2). Loss of ^{137}Cs obtained from water was rapid and exhibited little thermal dependence (Fig. 2C, Table 2). ^{137}Cs obtained by this route was depurated most quickly of the three radioisotopes examined, with at least 67% being in the CI pool and only 11% (12°C) and 14% (2°C) in the most slowly exchanging pool (CIII).

DISCUSSION

Our results indicate that temperature has an appreciable effect only on the proportion of ^{241}Am obtained from food in the slowest exchanging pool, with a greater fraction in this pool at 12°C than at 2°C. That is, the assimilation efficiency of ingested ^{241}Am was significantly higher at 12°C than at 2°C. All other thermal effects on efflux rates and distribution in the different pools of ingested radioisotopes, even when statistically significant, were very small.

Temperature also had no appreciable effect on loss of any of the radioisotopes obtained from water. The dissection data indicate that most of the isotope from this source in these relatively short-term exposures is on the shell. Longer term exposures might have resulted in more uptake by soft tissues, but in general many isotopes obtained by bivalves from water are located primarily on shell even after longer exposures (Bjerregaard *et al.*, 1985; Fisher and Teyssié, 1986; Fisher *et al.*, 1996).

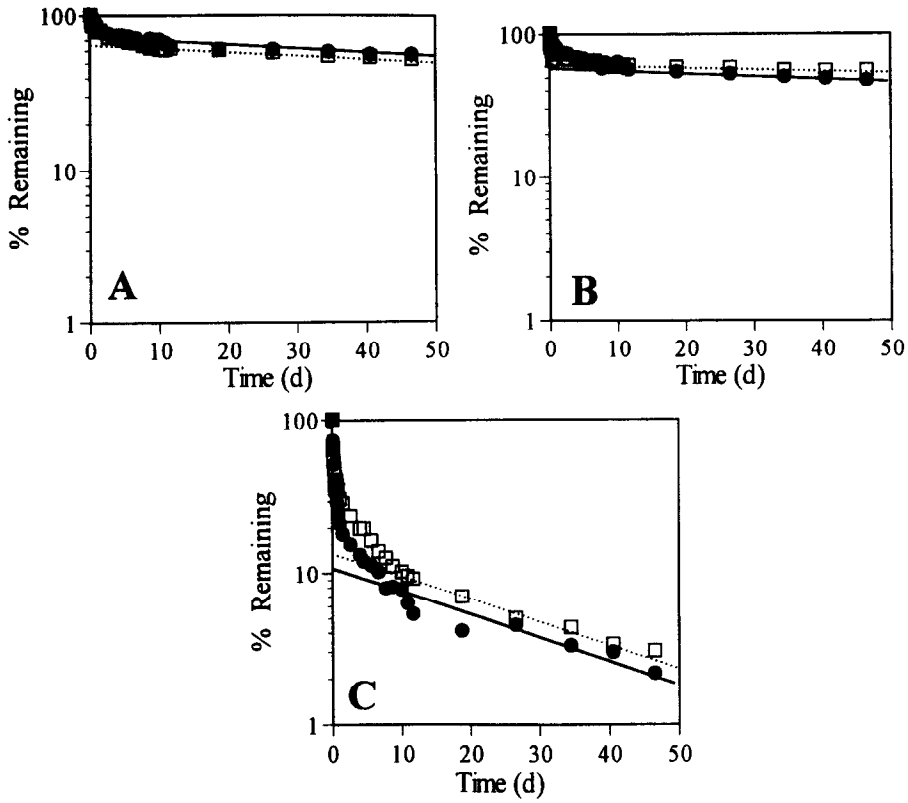

Fig. 2. Loss of ^{241}Am (A), ^{57}Co (B), and ^{137}Cs (C) by *Macoma balthica* exposed from radiolabeled water at 2°C (open squares) and 12°C (closed circles), expressed as the percent of the radioactivity remaining in the clams at the beginning of the depuration period. Regression lines indicate the best fit for each of the radioisotope pools in the clams. For descriptions of pools, see Table 2.

The increase over time in the fraction of total ^{241}Am and ^{57}Co content in the shell (following uptake from food at 12°C) suggests more efficient retention of minor amounts of isotope adsorbed to shell (derived from dissolved radioisotopes which had desorbed from the radiolabeled diatoms during the feeding) in comparison to soft parts. This would tend to increase the percentage of total body radioactivity in the shell as the animals depurate (Bjerregaard *et al.*, 1985). The fact that some portion of the long-term pool from food is located on the shell means that the assimilation efficiencies measured in these experiments represent an upper limit to amounts actually retained in soft tissues from food exposure.

The lack of any phytoplankton accumulation of ^{137}Cs, and its rapid loss by clams when obtained from water, are consistent with the observations of very low concentration factors for this radionuclide in marine organisms (IAEA, 1985). Although the short-term exposures in these experiments do not accurately replicate long-term exposure in the field, even extended experiments (6 months) have demonstrated that Cs concentration factors in clams are very low (3–5: Harrison, 1972). Thus clams are not likely to serve as a major conduit for bioaccumulation of Cs in marine food chains. Other experiments suggest that *Macoma* in natural sediment (rather than in water as in these experiments) have long-term

Cs concentration factors which are ≤ 1, further suggesting that clams would not accumulate this element efficiently from either food or water (I. Stupakoff, C. Gagnon and N. Fisher, unpublished data). The high levels of K^+ and Na^+ present in seawater competitively inhibit Cs^+ uptake by phytoplankton (Avery *et al.*, 1992; Hutchins *et al.*, 1996*a*), preventing substantial buildup of Cs radioisotopes in Arctic marine biota. Even in freshwater, Cs^+ uptake by diatoms is inhibited by low levels of alkali earth metal ions, but in the absence of these competing ions Cs concentration factors in diatoms can reach 10^4 (Fisher, unpublished data). Thus, Cs generally does not accumulate efficiently in marine food chains. This element does, however, display considerable trophic transfer in terrestrial ecosystems of the Arctic through lichen–caribou– human transfer (Hanson, 1967).

Uptake and loss kinetics of isotopes of both soft tissues and shell are important because many predators (e.g. walrus) ingest both parts of this soft-shelled bivalve. However, Arctic temperatures appear to have only minor effects on the individual processes that govern such kinetics. Among the effects of Arctic temperatures, the only substantial effect was that colder temperatures reduced the assimilation efficiency, and therefore the uptake, of ^{241}Am by *M. balthica* from diatom food. Relatively high assimilation efficiencies (AE) have been reported previously for *M. balthica* fed ^{241}Am-labeled diatoms (33–41%, Luoma *et al.*, 1992; Reinfelder *et al.*, in press), especially compared to assimilation by mussels (Wang and Fisher, 1996). The AE at 12°C reported here (26%) for *M. balthica* is similar to the values observed in the earlier experiments at warmer temperatures, while reducing the temperature to 2°C resulted in less than one-half the assimilation. Nearly all of the ^{241}Am ingested at low temperatures was egested; in contrast, temperature had no appreciable effect on assimilation of ^{57}Co.

The present experiments employed relatively short exposures, as well as relatively short depuration periods. Proportionation of elements among assimilated kinetic compartments in marine organisms is dependent upon exposure time (Van Weers, 1973; Cutshall, 1974); therefore the proportion of ingested ^{57}Co in CII, for example, was probably affected by the exposure regime. However, the rate constants of loss should not be affected by exposure time, provided time is sufficient for isotope exchange into all physiological compartments. The physiological turnover rates in these experiments are similar to those observed in many previous studies (Wang *et al.*, 1996) for a number of bivalve species under temperate conditions.

These results suggest that *Macoma* would be less effective as a bioindicator of trophic exposure to highly particle-reactive nuclear waste isotopes such as ^{241}Am (and possibly chemically similar elements as well) than some other common Arctic benthic organisms such as the macroalga *Fucus* (Boisson *et al.*, in press) or sea stars (asteroid echinoderms) which retain as much as 57% of ^{241}Am ingested with food (Hutchins *et al.*, 1996*a*). The somewhat higher AE for ^{57}Co suggests that this species would be a more effective bioindicator of exposure to radioactive activation products (most of which are transition metals) and heavy metals, and this bivalve has been used extensively as a sentinel of metal exposure in temperate habitats (Thomson *et al.*, 1984; Luoma *et al.*, 1985).

In these relatively short-term experiments radioisotope tissue distributions were tightly correlated with source. If differential tissue partitioning after long-term exposures from food and water is also the case, dissections of field-collected *Macoma* could provide valuable information about the importance of dissolved and food pathways in contaminated ecosystems. Our dissection results support earlier work suggesting that isotope concentrations found mostly in the visceral mass can be taken as evidence that the

primary exposure route is through food, while radioactivity obtained from water sources should be located almost entirely on the shell (Bjerregaard *et al.*, 1985; Fisher and Teyssié, 1986). Such information would be less useful for elements (such as Cd) which are significantly accumulated in soft tissues from water but not on shells (Wang *et al.*, 1996; Fisher *et al.*, 1996).

The relatively small effects of temperature found here suggest that seasonal changes in contaminant retention in temperate regions may be tied to season-specific biological processes such as spawning or growth more than temperature effects on digestive processes or contaminant geochemistry. Seasonal variability in body concentrations of Ag, Cu, and Zn have been reported in San Francisco Bay *Macoma* (Luoma *et al.*, 1985; Cain and Luoma, 1986, 1990) and in Baltic mussels (Dahlgaard, 1986). Metal concentrations were generally higher in animals collected during winter, and correlated with seasonal changes in soft tissue weight (Cain and Luoma, 1986, 1990). The opposing effects of temperature on different processes may explain the relatively ambiguous results sometimes reported for such experiments. Temperature effects on contaminant assimilation and retention by *Macoma* need to be considered along with other environmental variables in any area with pronounced seasonality. It is also possible that there could be effects of genetic adaption of polar and temperate clam populations on temperature control of isotope retention, and future experiments comparing populations from contrasting regimes should be carried out.

This work supports the findings of Hutchins *et al.* (1996*a*,*b*) and Boisson *et al.* (in press) that retention of at least some nuclear waste isotopes can differ between Arctic and temperate marine regimes, although effects were relatively small in *Macoma*. The extent to which these temperature- dependent release rates ultimately reflect differences in bioconcentration factors of these radionuclides between polar and temperate waters depends on the net outcome as opposing kinetic influences are manifested over time. Recent estimates of radionuclide concentration factors in polar marine invertebrates are, with a few exceptions, comparable to concentration factors in temperate-zone animals (IAEA, in prep.). This suggests that risk assessment models, in the absence of direct data, may be able to extrapolate concentration factor data, at least to the same order of magnitude, from other ecosystems to Arctic organisms for long-lived radionuclides.

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