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RADIOCAESIUM ELIMINATION IN THE YELLOW-BELLIED TURTLE (*PSEUDEMYS SCRIPTA*)

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SUMMARY

(1) Radiocaesium elimination in *Pseudemys scripta* Schoepff followed a typical exponential decay curve, with no difference in elimination rate constants between turtles kept indoors in a controlled environment chamber and others kept outdoors in an experimental pond.

(2) Radiocaesium elimination rate constants ranged from $0 \cdot 0028$ to $0 \cdot 0138$ day^{-1} ($\bar{x} = 0 \cdot 0072 \pm 0 \cdot 0044$ (S.E.) day^{-1}).

(3) There was no significant relationship between radiocaesium elimination rate constant and sex of the turtle.

(4) There was a positive exponential relationship between turtle body mass and radiocaesium elimination rate constants.

(5) There was a positive correlation between turtle body mass and the initial body burden of the turtle.

(6) Iterative regressions of the elimination data showed that 12–13 weekly determinations of ^{137}Cs total body burdens were necessary to adequately estimate the ^{137}Cs elimination rate constant of *P. scripta*.

INTRODUCTION

The recent accident at the Chernobyl nuclear facility in the U.S.S.R. demonstrates the disastrous potential of environmental contamination by released radionuclides (Hohenemser *et al.* 1986a,b; Medvedev 1986; Petersen, Landner & Blanck 1986). In such accidents, populations of domestic animals and wildlife inhabiting the contaminated areas may become important vectors for radionuclide spread into human food webs (Jenkins & Fendley 1968; Jenkins, Monroe & Golley 1969). Because of this fact, studies should be made to quantify the uptake, cycling and compartmentalization of various radionuclides (especially those produced as fission products or used as nuclear fuels). Such studies are essential for determining the fate of these contaminants as they enter an ecosystem, as well as their potential effects on the inhabitants and surrounding communities.

Studies of the dynamics of radiocaesium (in this case principally ^{137}Cs) elimination are especially useful for several reasons: caesium, as a chemical analogue of potassium, has a ubiquitous distribution within the body, including edible skeletal muscle. Counting techniques for the detection and quantification of radiocaesium do not require sacrifice of the animal, and thus permit repeated measurements of the same individual over time. The long physical half-life of ^{137}Cs ($30 \cdot 0$ years) ensures its persistence at measurable levels over

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the course of long-term experiments. Finally, ^{137}Cs is a major nuclear fission product and is present in detectable quantities in a number of organisms in many contaminated aquatic ecosystems. Caesium-137 is, in fact, the most important long-lived contaminant released throughout eastern Europe by the Chernobyl accident (Hohenemser *et al.* 1986a,b; Medvedev 1986; Petersen, Landner & Blanck 1986).

The species used in this study was the yellow-bellied turtle (*Pseudemys scripta* Schoepff), which is an abundant semi-aquatic inhabitant of many aquatic ecosystems of the south-eastern U.S.A., and is typical of many semi-aquatic vertebrates which may act as radionuclide vectors from contaminated aquatic areas to adjoining terrestrial or other aquatic habitats. Overland movements of *P. scripta* seeking mates or nesting sites may exceed 1 km (Morreale, Gibbons & Congdon 1984). It is also a long-lived animal and can thus accumulate considerable radionuclide body burdens during its lifetime (this may especially be true for radionuclides that are calcium analogues, e.g. [90]Sr and [226,228]Ra, because of the high demand for calcium salts for shell formation). *P. scripta* may also serve as an occasional dietary item (even if only as a novelty) for certain human populations (Scott, Whicker & Gibbons 1986).

Because of the potential hazards attending the introduction of radionuclides into the environment, most studies of radionuclide uptake and accumulation by free-living organisms have been based on laboratory-determined rates for the isotope in question, using the equation of Davis & Foster (1958):

$$Q_t = Q_e(1 - e^{-(\beta + \lambda)t}) \tag{1}$$

where Q_t is the total radionuclide body burden (TBB) of the organism at some time (t), Q_e is the TBB of the organism at equilibrium, β is the elimination rate constant for the isotope, and λ is the radioactive decay constant for the isotope. Because a true equilibrium will only be reached after infinite time, a practical equilibrium is considered to have been reached when $Q_t = 0.9Q_e$. The time (t) required to achieve this practical equilibrium can be calculated as:

$$t = -\frac{\ln(0.1)}{\beta + \lambda} \tag{2}$$

Because of the long half-life of ^{137}Cs relative to its biological half-life, the physical decay of this isotope may generally be disregarded, and the elimination rate constants, biological half-lives (T_b) and times to 0.9 of equilibrium presented may be considered the effective values.

In ectothermic organisms such as *Pseudemys scripta*, metabolic rates, and therefore feeding and excretion rates, fluctuate with variations in temperature. This makes it likely that environmental variables will have a strong effect on radionuclide elimination rates in such animals. Reichle, Dunaway & Nelson (1970) showed that the retention of ^{137}Cs by soft tissues was directly related to metabolic activity in a number of species, suggesting that, in ectotherms, the excretion curve will provide predictive information concerning the uptake curve under field conditions only if behaviourally thermoregulated body temperature and food intake are either the same under both field and laboratory conditions or can be corrected for statistically. This study was designed to determine whether the radiocaesium elimination rates of *P. scripta* in the field may be estimated satisfactorily under laboratory conditions if body temperature and food intake are held as constant as possible between the two treatments.

STUDY AREAS AND METHODS

This study was conducted using laboratory facilities and adjoining field enclosures of the Savannah River Ecology Laboratory (SREL), at the Savannah River Plant (SRP), a 750-km^2 nuclear production and research facility administered by the U.S. Department of Energy and located *c.* 20 km south of Aiken, Aiken Co., South Carolina, U.S.A.

Fifteen adult *Pseudemys scripta* were trapped from waste-disposal seepage basins on the SRP for use in the study. These basins contain higher than normal concentrations of ^{137}Cs as a result of the operation of the nuclear industrial facilities nearby. Turtles used in the study included six males ($\bar{x}$ body mass = 769 ± 105 (S.E.) g), and nine females ($\bar{x}$ body mass = 1491 ± 156 (S.E.) g). The fifteen turtles were separated into two treatment groups. Group 1 consisted of two males ($\bar{x}$ body mass = 749 ± 201 (S.E.) g) and five females ($\bar{x}$ body mass = 1592 ± 234 (S.E.) g), which were placed in individual water-filled 14-l plastic containers inside an Environator Model E3252 controlled environment chamber (Custom Controls, Inc., Warren MI). The light–dark cycle was adjusted weekly to maintain the same photoperiod as the current outdoor daylight, and the temperature was set to 28 ± 2 °C. Standora (1981) investigated the thermal relationships of *P. scripta* inhabiting two habitats on the SRP and found that adult turtles of this species maintained a deep body temperature of 26–32 °C during 61% of their active period in the summer, with a mean deep body temperature of 28 °C. These data allowed the controlled environment chamber to be set to a comparable temperature. An appropriate temperature setting would otherwise have been difficult to determine, as preferred temperatures selected by turtles in a laboratory thermal gradient differ greatly from the temperatures that can be maintained in the wild (Avery 1982; Spotila *et al.* 1984).

The remaining eight turtles (Group 2), consisting of four males ($\bar{x}$ body mass = 779 ± 144 (S.E.) g), and four females ($\bar{x}$ body mass = 1366 ± 213 (S.E.) g) were placed in an outdoor experimental pond (Pond F) from 23 April to 26 August 1986. Pond F, 18 × 21 × 9 m maximum depth, was the pond used by Scott, Whicker & Gibbons (1986) to study seasonal effects on elimination rate in this species. Maximum and minimum temperature data were periodically recorded from this pond and from Pond C, a similar artificial pond nearby. Both ponds had continuous flow-through water supplied from a well. During August, Pond C water showed a mean daily maximum of 30 ± < 1 °C (S.E.) (range = 28–32 °C), and a mean daily minimum of 25 ± < 1 °C (S.E.) (range = 24–26 °C). Weekly readings from a maximum–minimum thermometer at the bottom of Pond F (3 m deep) showed a range of weekly maxima of 22–26 °C and weekly minima of 17–20 °C. Weekly readings from a similar thermometer placed on the north shore of Pond F (southern exposure) showed a range of maxima of 35–50 °C and a range of minima of 15–40 °C. These measurements represent the probable maximum and minimum temperatures to which the Group 2 turtles were exposed during the study. Air temperature data for the Savannah River Plant were obtained from a nearby weather station. The average air temperature maxima/minima (and monthly average temperature) for the months of the study were: 27·91/10·33 (19·12) °C (April), 30·66/16·45 (23·56) °C (May), 34·52/21·83 (28·18) °C (June), 37·56/23·41 (30·48) °C (July), and 32·22/21·20 (26·71) °C (August).

Turtles in both groups were maintained on a weekly diet of 100 g whole fish and 25 g commercial dry dog food per turtle throughout the study. Aquatic macrophytes (principally *Bacopa caroliniana* Walt., *Brasenia schreberi* Gmel., *Nymphaea odorata* Ait. and *Utricularia* spp.) were collected from ponds in Aiken County, SC, and were provided

to all turtles as food *ad lib*. during the study. These macrophyte species were determined by Parmenter (1980) to be the most common macrophyte dietary items of *Pseudemys scripta* collected from the Aiken Co., SC, area. The macrophytes from these ponds were counted using the same gamma-counting equipment used for the turtles in the study, and showed no elevated concentrations of any gamma-emitting radionuclides compared with laboratory background (M. S. Kelly, personal communication).

A Canberra 8100 MCA multichannel pulse-height analyser with a 15-cm diameter × 10-cm high NaI(T1) crystal was used to determine the turtles' ^{137}Cs total body burdens (TBB). Every 7 days, the turtles were removed from their treatment locations and transported to the laboratory. All female turtles were palpated to determine whether shelled eggs were present, as egg laying would represent another, probably very different, ^{137}Cs elimination pathway and rate, compared with non-reproductive depuration. No shelled eggs were noted in any of the females at any time during the study, however, and the observed ^{137}Cs losses in these animals were therefore assumed to represent that due to non-reproductive depuration alone. Each turtle was weighed, double-wrapped in two 46 × 61 cm polyethylene bags, and taped to restrict leg and head movements. The turtle was then placed carapace-down in a lucite cradle centred over the NaI(T1) crystal inside a lead-brick counting chamber and counted for 15 min. The region of interest (ROI) for ^{137}Cs was defined as 598–728 keV, and the amplifier was checked by making 1-min counts of a ^{137}Cs source before and after background counts and before each turtle was counted. The amplifier gain was adjusted as necessary to ensure that the peak energy for the ^{137}Cs ROI remained centred at 662 keV.

Because ^{90}Sr was also known to be present in the turtles from this area, and because ^{137}Cs and ^{90}Sr contribute to each other's ROI, bremsstralung X rays (70–180 keV) produced by ^{90}Sr beta particle interactions were also recorded. The counting data were corrected for these contributions and for background radiation using background counts taken the same day, and the resulting ^{137}Cs net count rate and standard deviation (counts s^{-1}) were calculated for each turtle. The count yield (counts disintegration^{-1}) for each turtle was calculated according to procedures described by Towns (1987). The ^{137}Cs TBB in Bq was determined for each turtle by dividing the net ^{137}Cs counts by the count yield. The standard deviation of the net ^{137}Cs counts was converted to activity by the same method, and was < 0·1% of the TBB in all samples and was therefore considered to be insignificant. A more significant source of counting error was due to differences in geometry resulting from the non-replicability in wrapping the turtle and aligning it on the NaI(T1) cystal. The magnitude of this error was determined by making six successive counts of the same turtle, removing it from the crystal and re-wrapping it between counts, and comparing the resulting standard deviation with the mean estimated from six successive counts taken from the same turtle without removing and unwrapping the turtle between counts. This procedure allowed an estimation of the total counting standard deviation (i.e. the counting standard deviation due to non-replicable geometry combined with the counting standard deviation due to random disintegration of ^{137}Cs mentioned above). This total counting standard deviation was only 2·5% of the mean TBB of the turtle, and did not change significantly over the course of the experiment.

Potential contributions to the measured ^{137}Cs counts from radionuclides other than ^{90}Sr were also examined. Above-background levels of ^{214}Bi, a daughter product of ^{226}Ra decay, had earlier been noted in *Pseudemys scripta* collected in certain localities near the SRP (notably Aiken State Park, Aiken Co., SC). Some turtles from this locality exhibited ^{226}Ra body burdens > 56 times the ^{226}Ra background level in the SREL turtles. This

probably represented bioaccumulation of naturally occurring ^{226}Ra associated with the decay of uranium in the area. As soils in the region tended to be sandy and nutrient poor, any ^{226}Ra present was probably incorporated into the shells of the turtles at a higher concentration, because shell formation places a high calcium demand on these animals. Because ^{214}Bi has a γ photon energy similar to ^{137}Cs (601 vs. 662 keV), any ^{214}Bi in the turtle would contribute to the measured ^{137}Cs TBB. To determine the potential for significant ^{214}Bi contribution to the ^{137}Cs counts in this experiment, all the turtles used in the study were counted for 1 h each on a 43-mm diameter × 46-mm high Li-drifted reverse electrode germanium semiconductor (Ge(Li)) detector coupled with a Canberra Series 85 multichannel analyser. This instrument was capable of separating the regions of interest for the two radionuclides. None of the turtles used in the study showed ^{214}Bi body burdens that were greater than background levels, so any ^{214}Bi contributions from these animals were assumed to be negligible. As other studies have shown a low ^{134}Cs:^{137}Cs ratio in other SRP habitats ($\approx 1:20$ for ^{134}Cs:^{137}Cs in the Steel Creek area of the SRP (Marter 1970)), no correction was made for potential ^{134}Cs contributions to the counts. Other γ-emitting radionuclides likely to be present on the SRP are even less common than ^{134}Cs, and have photon energy spectra greatly different from ^{137}Cs (Anderson, Gentry & Smith 1973).

RESULTS AND DISCUSSION

Animals whose radionuclide body burdens are at equilibrium with their environment typically show single-phase elimination curves because the contribution of the radio-nuclides in the gut contents are small relative to TBB (Kolehmainen 1972; Staton, Brisbin & Geiger 1974; Fendley, Manlove & Brisbin 1977). Animals receiving acute oral or intraperitoneal doses, however, generally show two-phase elimination curves composed of a rapid elimination of the radionuclide in the gut, followed by a slower elimination of the radionuclide from the body tissues (Golley, Wiegert & Walter 1965; Hakonson & Whicker 1969). The seepage basin turtles used in this study showed elimination curves intermediate between these two extremes, depending on how long they had occupied the basins. Initial ^{137}Cs concentrations for the turtles ranged from 0·9 to 27·0 Bq g^{-1} wet wt ($\bar{x} = 9·0 \pm 1·6$ (S.E.) Bq g^{-1}). No significant correlation was observed between ^{137}Cs elimination rate constant and initial ^{137}Cs concentration ($r = 0·33$; $t_{13} = 1·19$; $P = 0·26$). Radiocaesium losses in the first day after capture ranged from < 1 to 52% of the initial TBB. To ensure that only the tissue component of the elimination curves was calculated, no counts made in the first 5 days were used, thus allowing time for the gut contents to be cleared. Parmenter (1981) estimated that *Pseudemys scripta* required 2–3 days to allow gut clearance of a meat meal, and extra time was added to allow for possibly slower clearance of any vegetable matter present.

Regression analyses were performed using the model TBB $= \alpha\ e^{\beta[\text{time (days)}]}$ for each individual. These analyses showed highly significant decreases ($P \leqslant 0·01$ in all cases) for the long-term components of each turtle, with a high degree of predictive ability (all $r^2 \geqslant 0·95$). Representative elimination curves are shown in Fig. 1. Covariate analyses (Snedecor & Cochran 1967) showed no significant effects of either environmental treatment ($F_{1,202} = 0·02$; $P = 0·87$) or sex ($F_{1,202} = 2·68$; $P = 0·10$). One turtle in the indoor elimination treatment (Group 1) died after 5 weeks in captivity and was not included in the covariate analyses. The elimination rate constants of turtles of both sexes kept in both
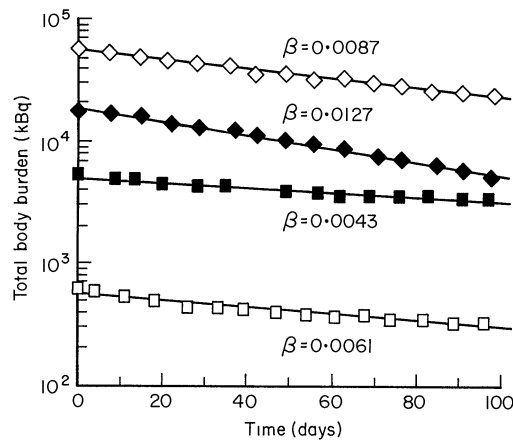
FIG. 1. Representative ^{137}Cs elimination curves for four representative turtles kept in a controlled environment chamber and in an outdoor experimental pond; (◊) and (□) = turtles in the indoor treatment group, (♦) and (■) = turtles in the outdoor treatment group. Straight lines represent significant least-squares fits to natural log-transformed data. β represents the biological elimination rate constant (day^{-1}).

TABLE 1. Elimination rate constants (β) for the two radiocaesium elimination treatments (indoor controlled environment chamber and outdoor experimental pond), calculated biological half-times (T_b) and times to 0·9 Q_e (equilibrium radiocaesium concentration), as determined by the Davis–Foster equation (Davis & Foster 1958)

Sex and (initial body mass) (g)	β (day^{-1})	S.E. β (day^{-1})	$\bar{x}$ and (95% C.I.) for T_b (days)	$\bar{x}$ and (95% C.I.) for time to 0·9 Q_e (days)
Indoor treatment				
♀ (1205·0)	0·0052	0·0002	133 (123, 145)	443 (410, 481)
♀ (1294·2)	0·0066	0·0003	105 (96, 115)	349 (320, 383)
♀ (1424·0)	0·0061	0·0010	114 (88, 160)	377 (293, 532)
♀ (2502·0)	0·0087	0·0003	80 (76, 84)	265 (251, 279)
♂ (548·7)	0·0028	0·0002	248 (217, 288)	822 (721, 957)
♂ (950·6)	0·0073	0·0002	95 (91, 99)	315 (302, 330)
Outdoor treatment				
♀ (854·5)	0·0043	0·0003	161 (143, 184)	535 (476, 612)
♀ (1244·3)	0·0104	0·0010	67 (57, 80)	221 (189, 267)
♀ (1867·7)	0·0138	0·0010	50 (44, 58)	167 (148, 192)
♀ (1497·5)	0·0137	0·0003	51 (49, 53)	168 (162, 175)
♀ (558·1)	0·0067	0·0010	103 (81, 142)	344 (271, 471)
♂ (652·5)	0·0040	0·0010	173 (119, 317)	576 (396, 1052)
♂ (702·9)	0·0083	0·0002	84 (79, 88)	277 (264, 292)
♂ (1202·6)	0·0093	0·0004	75 (69, 81)	248 (230, 269)
Pooled	0·0072	0·0022	96 (64, 194)	320 (213, 643)

indoor and outdoor elimination treatments were therefore pooled. Elimination rate constants of the fourteen surviving turtles are presented in Table 1.

A significant positive exponential relationship was found between ^{137}Cs elimination rate constants and initial body mass of the turtles ($r^2 = 0.35$; $F_{1,13} = 6.487$; $P = 0.026$). This could be interpreted as the result of inadequate food intake, larger turtles being more severely affected and metabolizing more skeletal muscle mass than smaller turtles, resulting in more rapid ^{137}Cs elimination. However, linear regressions of body mass against time showed no significant changes in body mass during the study for any of the turtles in the two elimination treatments, and it is therefore unlikely that the larger elimination rate constants of the larger turtles were the result of inadequate food intakes. This also indicated that the turtles were apparently not growing, so the differences in elimination rate constants were apparently not due to differential growth rates. When analysed separately, turtles in the indoor treatment showed no significant relationship between elimination rate constant and the initial body mass ($r^2 = 0.56$; $F_{1,5} = 5.126$; $P = 0.086$), while the turtles in the outdoor treatment showed a highly significant relationship ($r^2 = 0.65$; $F_{1,7} = 11.014$; $P = 0.016$). Figure 2 shows a plot of all turtles' elimination rate constants against body mass, as well as the fitted curve for the turtles in the outdoor treatment.

There was also a significant positive correlation ($r = 0.59$; $t_{13} = 2.56$; $P = 0.025$) between turtle body mass and the initial concentration of ^{137}Cs. A possible explanation for this correlation could be differing proportions of soft tissues to bone in turtles of differing sizes.

The estimates reported here for *Pseudemys scripta* radiocaesium elimination rate constants ($\bar{x}$ $\beta = 0.0072 \pm 0.0022$ (S.E.) day^{-1}) are similar to those reported by Reichle, Dunaway & Nelson (1970) for one amphibian and several fish species, and are also comparable to those reported by Scott, Whicker & Gibbons (1986) for *P. scripta* in
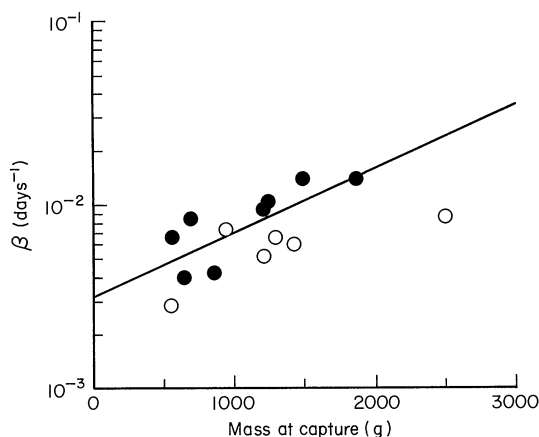

FIG. 2. Exponential regression of body mass at capture (g) against elimination rate constant (β); (O) = turtles in the indoor treatment group (Group 1), (●) = turtles in the outdoor treatment group (Group 2). The regression is fitted to data from the Group 2 turtles only, as no significant relationship between body mass and elimination rate constant was observed for the turtles in Group 1. $\beta = 3.3 \ 10^{-3} \ e^{\{0.0008[\text{mass (g)}]\}}$; $r^2 = 0.65$, $F_{1,7} = 11.014$, $P = 0.016$.
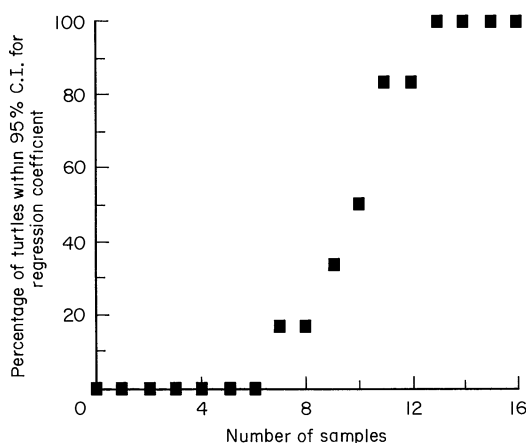
Fig. 3. Estimated time required to adequately estimate ^{137}Cs loss-rate in *Pseudemys scripta*. Iterative regressions of the elimination data were made on the six surviving turtles kept in the controlled environment chamber. In these regressions, each successive data point was added to the regression until the resulting slope was within the 95% confidence interval calculated for the analysis using all data points over the entire study for that animal. The percentage of turtles that were within their calculated confidence intervals is plotted for each sample.

summer ($\bar{x}$ $\beta = 0.0082 \pm 0.0006$ (S.E.) day^{-1}). The rate constants for the turtles of Scott, Whicker & Gibbons (1986), however, were based on only three or four observations per turtle, and were not determined by regression analysis, but by direct calculation from two successive data points. To determine the total elimination time required to adequately estimate ^{137}Cs elimination rate in *P. scripta*, iterative regressions were made on the six surviving turtles kept in the controlled environment chamber. In the regressions, each successive data point was added to the regression until the resulting slope was within the 95% confidence interval calculated for the analysis using all data points over the entire study for that same animal. Figure 3 shows the percentage of the six turtles whose elimination rate constant estimates were within these confidence intervals for each sampling period. It is apparent that at least twelve weekly samples are required for estimation of the ^{137}Cs elimination rate constant. The one turtle in Group 1 that died did so before this interval was completed, and for this reason was eliminated from the covariate analyses and the pooled estimate of the ^{137}Cs elimination rate constant for all turtles.

The similarity of elimination rates for males and females supports the results of earlier investigations on birds (Fendley, Manlove & Brisbin 1977) and mammals (Goldman *et al.* 1965; Stara 1965; Hakonson & Whicker 1969). However, the positive relationship between the elimination rate constant and the size of the turtle was surprising, as larger individuals would be expected to have lower mass-specific metabolic rates and smaller absorptive surface:volume ratios than smaller individuals (Parmenter 1981). In both endotherms and ectotherms, other investigators (Eberhardt 1967; Reichle, Dunaway & Nelson 1970; Staton, Brisbin & Geiger 1974; Fendley, Manlove & Brisbin 1977) have found a significant *negative* relationship between body size and elimination rate constant. The positive relationship was only present in the outdoor treatment group, suggesting that it is not a phenomenon of body size *per se*, but may be due to factors other than body

size. As has been mentioned above, this is difficult to explain on a strictly physiological basis (i.e. a relationship between body size and assimilation ability and/or metabolic rate). Parmenter (1981) found no effect of body size on digestive turnover time in *Pseudemys scripta*, despite a highly significant relationship between body size and intestine length, and he suggested that adults must move food through the gut faster than juveniles. If this is true, this more rapid passage of food could conceivably affect the ^{137}Cs elimination rates of the turtles through differing rates of ion exchange, but should still produce a more rapid loss of ^{137}Cs by smaller turtles because of a larger intestinal absorptive surface:volume ratio. It is therefore likely that individual elimination rates are more dependent on individual activity patterns, physical condition, age, and/or other factors that could not be identified in the study animals, and which may themselves be influenced by body size. This could account for the results of Scott, Whicker & Gibbons (1986), who found seasonal effects on ^{137}Cs elimination rate in *P. scripta* that could not be explained on the basis of temperature differences alone.

Considering the differences in variability of daily temperature régimes and in potential for physical activity between the two elimination treatment groups (fluctuating temperatures and freedom of movement in the experimental pond vs. relatively constant temperatures and confinement to small plastic containers in the controlled environment chamber), the lack of significant treatment effects might be considered surprising. Orr (1967) noted that ^{65}Zn elimination in the cotton rat (*Sigmodon hispidus* Say and Ord) was more rapid in the field than in the laboratory. However, as has been mentioned above, *Pseudemys scripta* are capable of maintaining a relatively constant deep body temperature during their active period (the majority of the day during the late spring and early summer). It is therefore likely that the mean body temperatures of the turtles in the two elimination groups were similar during much of the day. Any potential differences in elimination rates that might have resulted from differing temperature régimes might also have been offset by compensatory differences in physical activity between animals in the two groups. It should be noted, however, that variability in elimination rates among individuals was great. Other factors (e.g. body size, physical condition) may have introduced variation of much greater magnitude than that produced by the differing treatments. Such factors should be considered in future studies, but these results do suggest that it is possible to make estimations of radionuclide elimination in the controlled environment of the laboratory that are realistic estimations of such rates in free-living turtles in the field—a distinct advantage when considering the greater effort involved in periodically recapturing animals from field sites. It should now be possible (at least theoretically) to use these laboratory-determined β values to estimate field uptake rates and times to 90% of radiocaesium equilibrium ($0.9\ Q_e = -\ln(0.1)/\beta$). Table 1 shows the calculated biological half-times ((T_b) $= -\ln(0.5)/\beta$), and estimated times to $0.9\ Q_e$ for each individual, together with the pooled estimates for all turtles. The confidence intervals for the T_b and time to $0.9\ Q_e$ were calculated from the corresponding β values and associated standard errors before conversion to time periods. Although the T_b values are useful for comparing curves, Chew (1971) points out that they should not be averaged because they involve a reciprocal of β; thus the average $T_b \neq (0.693/\text{average } \beta)$. Standard error and confidence limits can, however, be calculated for a β value, and then transformed into confidence intervals for T_b and time to $0.9\ Q_e$.

The estimates presented here for T_b and time to $0.9\ Q_e$ may not reflect actual radiocaesium uptake rates in the wild. The Davis–Foster model (1958) depends upon two main assumptions: that the rate of radionuclide intake remains constant, and that the

biological elimination rate constant does not change. Scott, Whicker & Gibbons (1986) have demonstrated seasonal variation in elimination rate constants in *Pseudemys scripta*. It is also unlikely that the assumption of a constant rate of radionuclide intake is attainable in the field, particularly for ectothermic animals (such as *P. scripta*), which may undergo prolonged periods of winter dormancy. In particular, it should be noted that the majority of the estimates of times required to reach equilibrium exceed (some by as much as threefold) the number of days per year that are generally warm enough to sustain continual activity and feeding in this species at this latitude (*c.* 250 days, although brief periods of activity can occur on warm days during the winter dormancy period). This suggests that most turtles would require > 1 year to reach ^{137}Cs equilibrium after first arriving in a contaminated habitat. In the light of this result, it is apparent that these estimates now need to be verified with field uptake data to confirm that the rate (and pattern) of radiocaesium uptake predicted by the Davis–Foster equation is in fact an adequate description of radiocaesium uptake and concentration by this species under natural conditions. If uptake rates cannot, in fact, be predicted satisfactorily from elimination rates, the turnover rate of radionuclides for other organisms (particularly ectotherms) may not be as easily determined as first-order kinetics models would suggest. When these principles are applied to migratory fish or wildlife species that are dietary items of humans, this knowledge becomes crucial in determining the extent to which such animals may become or remain unfit for human consumption following episodes of radionuclide contamination. Reliable estimates of radionuclide uptake are also critical in determining the total integrated body burden and total committed radiation dose to the species in question, as well as to predators of that species. Such information is of great importance in assessing the likely long-term consequences of radionuclide contamination of ecosystems.

ACKNOWLEDGMENTS

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