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ACCUMULATION AND RETENTION OF CESIUM^{137} BY MARINE FISHES

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ABSTRACT

Accumulation and retention of Cs^{137} by marine fishes were followed in laboratory experiments. Comparisons were made between accumulation directly from the water and from ingested doses. Cs^{137} was accumulated readily through both pathways by all fish tested.

Cesium^{137} concentration per unit weight in postlarval flounder (*Paralichthys dentatus*) was shown to vary inversely with changes in the rate of weight increase. This was attributed to the disparity between rate of accumulation and rate of weight increase.

Accumulation of Cs^{137} was generally similar in tissues of croaker (*Micropogon undulatus*), bluefish (*Pomatomus saltatrix*), and little tuna (*Euthynnus alleteratus*). These tissues, listed in order of highest concentration, were heart, liver, spleen, kidney, gills, gonad, muscle, skin and scales, blood, and bone.

Whole-body retention of Cs^{137} by postlarval flounder was expressed as two rate functions with biological half-lives of 5.3 and 36.9 days. Retention by certain tissues of croaker was expressed as multiple rate functions as follows: Skin, three rate functions with biological half-lives of 6.2, 26.2, and 290.0 days; muscle, two rate functions with biological half-lives of 34.8 and 94.7 days; liver, four rate functions with biological half-lives of 0.7, 4.2, 24.1, and approaching infinite days; and gonad, two rate functions with biological half-lives of 13.4 and 911.0 days.

ACCUMULATION AND RETENTION OF CESIUM^{137} BY MARINE FISHES

By John P. Baptist and Thomas J. Price, *Fishery Research Biologists*
Bureau of Commercial Fisheries

The problem of fishes being polluted by radioactive materials released into the aquatic environment [1] becomes increasingly important with the continued development of atomic energy. A major source of pollution has been the detonation of nuclear weapons which released large quantities of radionuclides into the environment (Revelle and Schaefer, 1957). These have made a negligible contribution to the total radioactivity of the sea, but have temporarily contaminated the test areas (Kawabata, 1955; Donaldson and others, 1956; Seymour and others, 1957). There is also a possibility that the oceans may be used for the disposal of concentrated radioactive wastes from the increasing number of atomic reactors (Revelle and Schaefer, 1957). This possibility, along with the testing of nuclear weapons and the present dumping of low-level wastes, emphasizes the need for evaluation of hazards to man through fisheries. Such an evaluation can be made only with a knowledge of the disposition of these radionuclides in the biology of marine organisms.

Radioactive Cs is readily accumulated in the tissues of animals and is therefore a hazard to man when it is released into a marine environment containing animals used as food. Krumholz (1956) found that about 75 percent of the radioactivity in soft tissues of bluegills and crappies in a contaminated lake resulted from Cs^{137}. Suckers in the Columbia River accumulated substantial amounts of this radionuclide in muscle (Davis and others, 1958). Small amounts of Cs^{137} were found in fish muscle, marine algae and fish-eating birds during a resurvey of two atolls of the Marshall Islands approximately 1 year after "Operation Castle" (University of Washington, 1955). Pendleton and Hanson (1958) followed the accumulation of Cs^{137} through food chains in aquatic environments. They reported that carnivorous vertebrates had higher concentration factors than omnivores. Working with invertebrates, one of the authors, T. J. Price (unpublished data), found that clams and oysters concentrated Cs^{137} six times over that by sea water in 20 days, whereas muscle of scallops had a concentration factor of 10 in 10 days.

The metabolism of radioactive Cs by domestic and laboratory animals has been studied by various workers. Weeks and Oakley (1955) fed rats regularly with Cs^{137} as an inorganic solution, biologically incorporated in plant material, and mixed with plant material. Their results indicated that absorption was not affected by the form in which it was fed and that the greatest accumulation occurred in muscle. While studying the metabolism of Cs^{137} in rats, cattle, sheep, swine, and chickens, Hood and Comar (1953) found a high degree of absorption of ingested Cs^{137}, long-term retention and similar concentration patterns among species and among tissues. Ballou and Thompson (1958) administered Cs^{137} to rats both in single doses and over a long period. They found that predictions of the long-continued buildup, based on single dose data, were in close agreement with the results from the prolonged feeding experiment.

The present experiments were undertaken to follow the accumulation of Cs^{137} by fish, both from sea water and from ingested doses; and to determine its biological half-life ($t_{1/2}$), which is the time required for an organism or tissue to lose one-half of a given substance by biological elimination.

METHODS AND MATERIALS

Fish were collected in the vicinity of Beaufort, N.C., and included the following species: postlarval summer flounder, *Paralichthys dentatus* (Linnaeus), weighing 17.6–48.6 milligrams; Atlantic croaker, *Micropogon undulatus* (Linnaeus),

[1] This investigation was conducted as part of a research program sponsored jointly by the U.S. Bureau of Commercial Fisheries and the U.S. Atomic Energy Commission.

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34–204 grams; bluefish, *Pomatomus saltatrix* (Linnaeus), 250–350 grams and little tuna, *Euthynnus alleteratus* (Rafinesque), 5.4–6.1 kilograms. Fish were weighed immediately prior to radioactivity measurements. Flounder were kept in small indoor tanks and fed nauplii of the brine shrimp, *Artemia salina*. Croaker, bluefish, and little tuna were kept in large outdoor tanks and all except little tuna were fed cut fish. The latter would not accept food while in captivity, and the only experiment utilizing this species was limited to 8 days.

The carrier-free Cs^{137} used in the present experiments was obtained in the form of CsCl in 0.12N HCl from the Oak Ridge National Laboratory, Oak Ridge, Tenn. It has a half-life of 30± 3 years and is in secular equilibrium with Ba^{137}, which has a half-life of 2.6 minutes.

EXPERIMENTAL PROCEDURE

Fish accumulate radioactive Cs by direct absorption from the water and by ingestion of food and water. Both pathways were followed in the present experiments. Radioactivity absorbed by tissues of fish kept in standing sea water containing a given concentration of Cs^{137} was measured (radioassayed) periodically. To determine the amount of absorption from the digestive tract, Cs^{137} was administered orally to fish which were kept in flowing sea water and radioassayed periodically.

Accumulation by absorption from sea water was followed in flounder and croaker. The water was first filtered through cotton to remove particles which might take up Cs^{137}. Frequent radioassay and renewal of the water insured a minimum variation of the Cs^{137} content and prevented a buildup of excretory products. The water was aerated and had an average salinity of 32±3°/oo. Twenty-nine flounder were kept in a battery jar containing 5 liters of sea water with a Cs^{137} concentration of 0.1 μc per ml. The jar was placed in a bath of flowing sea water to maintain a temperature within the range of that in the natural environment. During the experiment the temperature gradually increased from 8° to 18° C. Twenty-four croaker were kept in a tank containing 48 liters of sea water with

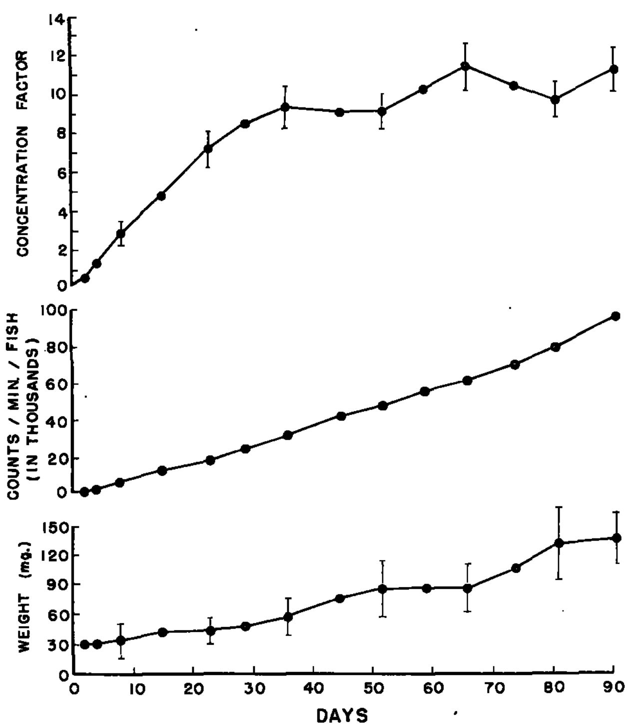

FIGURE 1.—Accumulation of Cs^{137} by postlarval flounder from sea water as influenced by growth rate. Upper curve is based on the ratio of radioactivity in fish to that in an equal weight of water. Center curve is based on radioactivity per individual. Lower curve represents mean weight of fish. Vertical lines are one standard deviation above and below curve.

a Cs^{137} concentration of 0.0005 μc per ml. and a temperature of 21±1° C.

The method selected for administering Cs^{137} orally was that most easily adapted to the particular species of fish. When croaker were used, the radionuclide was pipetted directly into the stomach. However, bluefish regurgitated the liquid, so each dose was changed to a solid by the following method: One-tenth ml. of the radionuclide was pipetted on a small piece of aluminum foil. Into this droplet powdered gelatin was sprinkled until it appeared dry on the surface. The foil was placed on a hotplate set at low heat until the preparation became clear. It was then removed from the hotplate, allowed to dry for about 4 hours and the dose was peeled from the foil and rolled into a cylinder. After drying overnight the dose became quite hard and was introduced into the esophagus of a bluefish by the use of forceps. Because of the extremely large mouth and throat of little tuna, the gelatin doses were first inserted into the body cavity of the pinfish, which in turn were fed to the little tuna by the use of forceps. The amount of Cs^{137} given varied from 0.4 to 1.0 μc per gram of fish. Since the Cs^{137} administered to fish was greatly diluted from the acid stock solution and the volume of each dose was only 0.1 ml., the pH of the contents of the fish stomachs was not significantly affected.

In measuring the Cs^{137} content of postlarval flounder, each fish was rinsed in a screw-cap vial containing 2 ml. of nonradioactive sea water, weighed, and radioassayed alive. By following this procedure it was possible to radioassay all of the flounder at each time interval.

Measurements of radioactivity in croaker or bluefish were averaged from four or five individuals per time interval, but only one little tuna was measured because of the difficulty in keeping a sufficient number alive. After careful dissection, small portions of certain tissues were excised from the same relative positions in all fish. These were placed in screw-cap vials, weighed on a precision balance and radioassayed. Blood samples were taken from the truncus arteriosus with a hypodermic syringe after first making an incision to expose the heart. In some instances both blood serum and whole blood were measured. Separation of the cells from the serum was accomplished by centrifuging the coagulated blood.

RADIOASSAY OF TISSUES

Gamma ray emission of tissues was measured with a well-type scintillation crystal in which 0.01 μc of Cs^{137} yielded a rate of 6,500 counts per minute. Counting rates were not influenced by biological separation of Cs^{137} and Ba^{137} since the short half-life of Ba^{137} permitted the return of secular equilibrium before the samples were radioassayed. All measurements were of required duration to insure a maximum standard deviation of 2 percent. Decay corrections were applied only when experiments exceeded 90 days. In accumulation experiments measurements of Cs^{137} are expressed either in counts per minute per unit weight of tissue, or as a concentration factor, the ratio of radioactivity in fish tissue to the radioactivity in sea water on a unit weight basis. When Cs^{137} was administered orally, all fish of a group were given the same quantity, and measurements of radioactivity in the tissues were corrected to a fish of standard weight. In retention experiments, measurements are expressed as percentages of the radioactivity present at zero time. All values are presented as averages.

RESULTS

ACCUMULATION

Accumulation of a radioactive substance by an organism occurs when the rate of uptake exceeds the rate of excretion. As stated previously, fish in the marine environment may accumulate Cs^{137} directly from sea water or from ingested food. Absorption through both pathways may occur either simultaneously or at different times, depending on the food habits or migratory patterns of the fish concerned. In the present experiments, absorption was followed through the two pathways independently so comparisons could be made between them.

Accumulation from sea water

Whole-body accumulation of Cs^{137} from sea water by postlarval flounder was followed during a period of 91 days. The experiment was begun with 29 fish, but the number was reduced to 24 by mortality during the first 14 days. One additional fish died during the remaining 77 days. The rate of accumulation was fairly uniform during the first 30 days (fig. 1). From the 30th to the 50th day the rate leveled off at a concentration factor of 9, accompanied by a slight increase in the average weight of the flounder. During the following 14-day period the amount of food given was reduced by approximately one-half. This resulted in a leveling off of the weight curve with a corresponding increase in Cs^{137} accumulation to a concentration factor of 11. When regular feeding was resumed and the average weight increased from the 64th to the 77th day, the Cs^{137} concentration in the fish actually decreased. Results during the final 14 days of the experiment were similar to those found during the period from the 50th to the 63d day.

The reduced rate of accumulation of Cs^{137} per unit weight during periods of rapid weight increase probably was the result of the fish increasing in mass more rapidly than Cs^{137} was accumulated. That is, the amount of Cs^{137} accumulated by new tissue was so small that the increase of radioactivity due to growth was not detectable, as indicated by the middle curve in figure 1, produced by plotting the radioactivity per fish rather than per unit weight. The result was, in effect, a "biological dilution" of the isotope. During periods of slow weight increase the opposite effect was evident apparently because the rate of accumulation exceeded the rate of weight increase.

Accumulation of Cs^{137} by muscle, liver, heart and spleen of croaker was followed during a period of 29 days, the last three tissues being grouped for each determination. Muscle accumulated the radionuclide at a uniform rate, reaching a concentration 4.5 times that of sea water after 29 days (fig. 2). Accumulation occurred more rapidly in liver, heart, and spleen than in muscle, but the rate decreased as the experiment progressed. These tissues had a concentration factor of 9 at the end of 29 days.

Accumulation from the digestive tract

Accumulation and tissue distribution of Cs^{137} by croaker following oral administration of single doses was determined over a 4-day period. Values were based on averages of four fish per time interval. Six hours after the dose was given only 15.4 percent remained in the digestive tract (table 1). The fact that the intestine did not contain more than 5 percent of the dose at any time plus the early appearance of the radionuclide in the organs and tissues indicated rapid absorption. Hood and Comar (1953) reported similar high absorption of Cs^{137} through the rumen walls of cattle.

Tissue concentration of Cs^{137} in the croaker dosed orally (fig. 3) was similar to that in croaker immersed in radioactive sea water. In both experiments, internal organs had rapid rates of accumulation initially, while muscle tissue had a slower rate. However, in the experiment in which croaker were kept in radioactive sea water, a constant supply was available, so that the

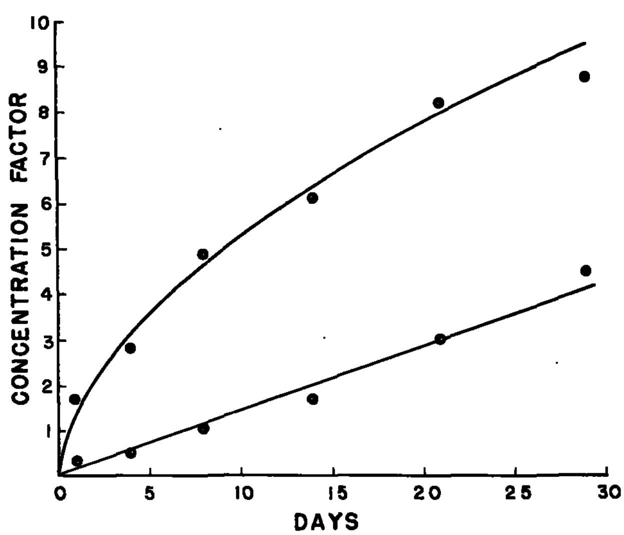

FIGURE 2.—Accumulation of Cs^{137} by croaker from sea water.
Upper curve: heart, spleen, and liver.
Lower curve: muscle.

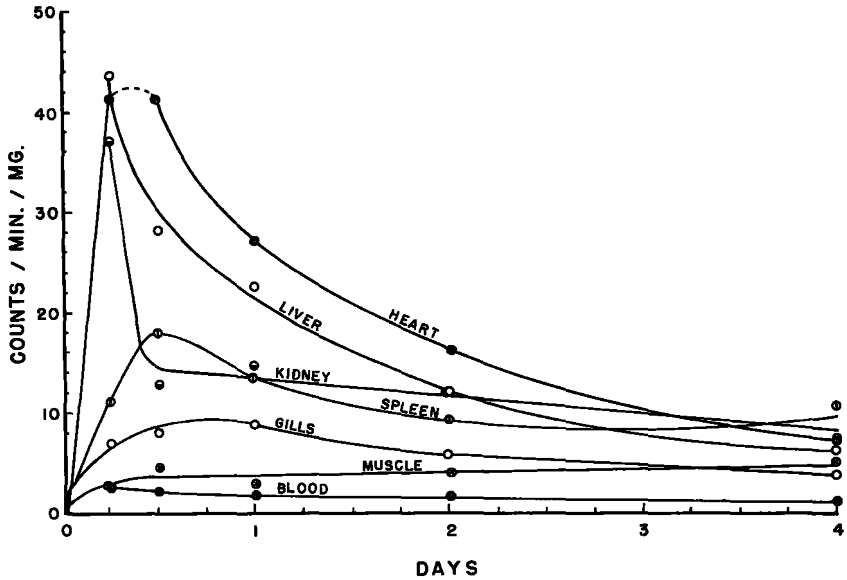

FIGURE 3.—Concentration of Cs^{137} in tissues of croaker following a single oral dose.

amount of Cs^{137} in the organs did not diminish. In the present experiment, the supply of Cs^{137} was limited by a single dose in the digestive tract. Consequently, instead of maximum levels of activity being maintained in the tissues, peaks of concentration were reached at certain time intervals following ingestion.

TABLE 1.—*Cs^{137} remaining in digestive tracts of croaker at intervals following oral administration*

Organ	Percent of dose remaining after—					
	0 day	¼ day	½ day	1 day	2 days	4 days
Stomach	100	7.1	6.2	6.1	3.5	2.3
Pyloric caeca	0	3.3	1.5	0.9	0.8	0.4
Intestine	0	5.0	3.1	2.3	2.1	1.4
Total	100	15.4	10.8	9.3	6.4	4.1

All tissues tested concentrated Cs^{137} to higher levels than blood, which maintained a relatively low and slowly decreasing concentration of the radionuclide. This decrease of radioactivity in the blood probably was an indication of excretion by all tissues tested, since blood serves as a transporting medium for them. The early accumulation by liver, kidney, heart, and spleen, along with the rapid loss from the digestive tract, indicates that the internal organs concentrated most of the radionuclide as soon as it became available in the blood. The accumulation of Cs^{137} by the gills was high during the first few hours, but leveled off and began to decrease 24 hours after dosage. Muscle, after an initial brief period of rapid uptake, accumulated the radionuclide at a slower but uniform rate while the available Cs^{137} became reduced in the digestive tract and the other tissues.

Accumulation and tissue distribution of Cs^{137} in little tuna from a single oral dose were followed during an 8-day period. As in the croaker, the internal organs took up the radionuclide at a fast rate, concentrating it over levels in the blood; muscle and gonad had slower rates and moderate levels of concentration, while the other tissues had relatively low concentrations (table 2). It is interesting that on the first day 99 percent of the Cs^{137} in the blood was located in the serum, while on the sixth day only 44 percent was in the serum and 56 percent in the cells.

The tissue distribution of Cs^{137} in bluefish was determined 24 hours after oral administration. The results of this test were generally similar to those found for croaker and little tuna (table 3).

TABLE 2.—*Concentration of Cs^{137} in different tissues of little tuna following a single oral dose*

Tissue	Counts/minute/mg. after—			
	1 day	3 days	6 days	8 days
Liver	4,761	2,473	1,813	1,358
Heart	3,214	1,652	1,322	821
Spleen	1,848	1,728	1,692	821
Kidney	1,643	1,356	932	499
Blood, whole	324	230	205	------------
Blood serum	322	145	90	------------
Muscle	241	352	457	403
Gonad	285	366	699	705
Bone	212	209	90	137
Eye	159	134	163	158
Brain	155	182	362	347
Skin	154	242	216	531

TABLE 3.—*Relative concentration of Cs^{137} in tissues of three species of marine fish 1 day after a single oral dose*

Tissue	$\frac{\text{cpm/unit wt. tissue}}{\text{cpm/unit wt. blood}}$		
	Croaker	Bluefish	Little tuna
Blood	1.0	1.0	1.0
Liver	12.5	5.9	14.6
Spleen	7.5	6.4	5.6
Kidney	8.0	4.9	5.1
Gonad	2.4	1.8	.9
Muscle	1.7	1.5	.7
Bone	1.1	1.3	.6
Skin-scales	1.1	.8	.5
Gills	4.9	2.1	---------------

RETENTION

Experiments were conducted in which whole-body retention of Cs^{137} by postlarval flounder and the retention by certain tissues of croaker were observed. Data were plotted against time on semilog paper as percentages of Cs^{137} present at zero time and analyzed by the standard kinetic approach usually applied to first-order reactions (Comar, 1955; Richmond, 1958). This procedure need not be discussed here in detail, but a brief description may facilitate presentation of the experimental results.

After fitting the curve to the retention data by inspection, the slope of the linear tail was more accurately determined by the method of least squares and extrapolated back to the y axis or zero time. The extrapolated values were subtracted from the corresponding values of the composite curve, and the differences were plotted on an expanded scale for greater accuracy. The linear tail of the new composite curve was extrapolated in the same manner, and the differences between the extrapolated values and composite values were plotted as before. This procedure was repeated until the final subtraction produced a straight line.

Analysis of the retention process by this method determines the number of exponential functions involved, the rate of removal per unit time by each function, and the amount of substance at zero time represented by each rate function. It is not to be inferred, however, that each function represents removal from a single compartment, since there may be intermediate steps involved or several compartments may be contributing to a single rate function.

TABLE 4.—*Retention of Cs^{137} by postlarval flounder and croaker, showing separation of composite curves into individual rate functions*

Fish and fish tissues	Components of retention curve [1]											
	a_1 percent	k_1 days	$(t_{1/2})_1$ days	a_2 percent	k_2 days	$(t_{1/2})_2$ days	a_3 percent	k_3 days	$(t_{1/2})_3$ days	a_4 percent	k_4 days	$(t_{1/2})_4$ days
Flounder, whole-body: per fish	34	0.1308	5.3	66	0.0188	36.9	--------	--------	--------	--------	--------	--------
per unit weight	67	.1024	6.8	33	.0149	46.4	--------	--------	--------	--------	--------	--------
Croaker tissues, per unit weight:												
Skin	87	.1118	6.2	10	.0265	26.2	3	0.0024	290.0	--------	--------	--------
Muscle	35	.0199	34.8	61	.0073	94.7	--------	--------	--------	--------	--------	--------
Gonad	86	.0517	13.4	3	.0008	911.0	--------	--------	--------	--------	--------	--------
Liver	61	1.0343	.7	37	.1631	4.2	2	.0288	24.1	0.4	$k \doteq 0$	$t_{1/2} \doteq \infty$

[1] From the equation $R = a_1e^{-k_1t} + a_2e^{-k_2t} + \ldots a_ne^{-k_nt}$ and $t_{1/2} = \frac{0.693}{k}$ (Richmond 1958).

The retention process may be expressed by the form

$$R=a_1e^{-k_1t}+a_2e^{-k_2t}+\cdots a_ne^{-k_nt}$$

in which $a_1, a_2, \ldots a_n$ and $k_1, \ldots k_n$ are the intercept and rate constants, respectively, of the individual or first-order components of the retention or elimination process (Richmond, 1958). Values of k were calculated by multiplying the slope of the line by 2.3, the slope being $(\log A_0-\log A)/t$ in which A_0 represents the amount of material at zero time and A the amount at time t. Biological half-life was determined by the form $t_{½}=0.693/k$ (Comar, 1955).

Whole-body retention

The retention of Cs^{137} by flounder which had accumulated the radionuclide for 3 months was followed over a period of 44 days. Water temperature varied between 22° and 26° C., and the average salinity was 32°/oo. Twenty-three flounder were radioassayed individually, and the values averaged for each determination. Mortality reduced the number of fish to 13 by the 37th day and to 8 fish by the last day.

The retention curve for postlarval flounder was composed of two exponential rate functions (fig. 4). The first component (A) contained 34 percent of the amount of Cs^{137} at zero time and had a $t_{½}$ of 5.3 days. The second component (B) contained 66 percent of the Cs^{137} at zero time and had a $t_{½}$ of 36.9 days. It is significant that the larger portion of Cs^{137} was represented by the slower moving component. In view of the experiments with croaker described earlier, this larger portion probably represented the influence of muscle. It should be remembered that these fish had been exposed to Cs^{137} for 3 months so there was ample time for a buildup of the radionuclide in muscle. Furthermore, muscle represents the largest mass of any single tissue.

The same data also were plotted on a unit-weight basis. As expected, the results were different because of changes in rate of weight increase (table 4). The first component contained 67 percent of the Cs^{137} at zero time and had a $t_{½}$ of 6.8 days. The second component contained 33 percent of the Cs^{137} and had a $t_{½}$ of 46.4 days. It is interesting to note that the slow-moving component represented the smaller portion. The reason for this difference is that during the period from the 24th to 44th day no significant change in weight occurred, but during the first 23 days there was an increase. The weight increase in effect produced an elimination rate largely influenced by "biological dilution" which was not evident in the period from the 24th to the 44th day. This resulted in a slower apparent elimination rate for the second component which indicated a small percentage when extrapolated back to zero time. Undoubtedly, the first curve based on the amount of Cs^{137} per fish presents the more reliable picture of whole-body retention by postlarval flounder.

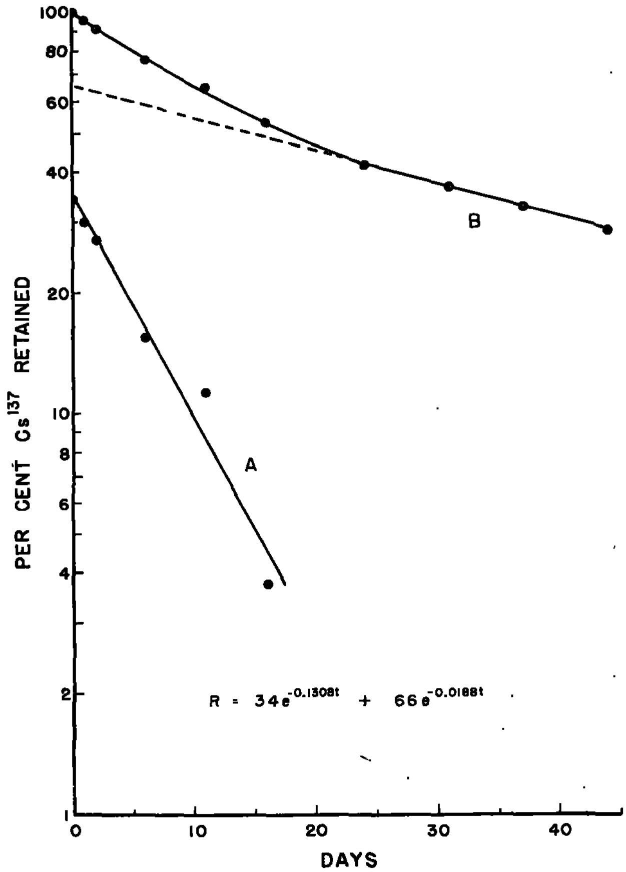

FIGURE 4.—Retention of Cs^{137} by postlarval flounder, showing separation of composite curve into two rate functions.

Tissue retention

Retention of Cs^{137} by selected tissues of croaker following administration of an oral dose was observed over a period of 219 days. The experiment was begun in May and completed in January, so that water temperatures gradually increased from 24° C. to a maximum of 32° C. during August, then decreased to a minimum of 10° C. at the end of the experiment. Salinity ranged from 30 to 35°/oo during the period of observation. Starting 24 hours after dosage, skin, muscle, liver, and gonad of sacrificed croaker were radioassayed periodically, and retention curves were drawn by inspection (fig. 5). These curves were then analyzed and replotted by the methods described above. The curve for skin is presented (fig. 6) as a typical example, and retention data on all the tissues are presented in table 4.

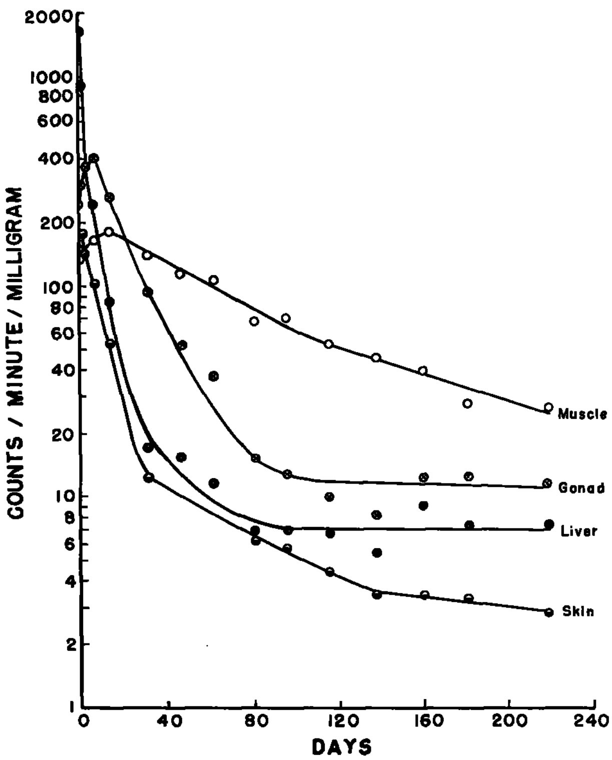

FIGURE 5.—Retention of Cs^{137} by certain croaker tissues following a single oral dose. Curves fitted by inspection.

The concentration of Cs^{137} by skin was relatively low at zero time as compared to the other tissues and decreased rapidly for several days. The retention curve consisted of three rate functions or components with $t_{1/2}$'s of 6.2, 26.2, and 290.0 days (fig. 6). These components represented 87, 10, and 3 percent of the amount of Cs^{137} at zero time.

Muscle continued to accumulate Cs^{137} until the 14th day, which was considered zero time in calculating retention rates. Although the concentration in muscle was relatively low in the beginning, the slow elimination rate resulted in a

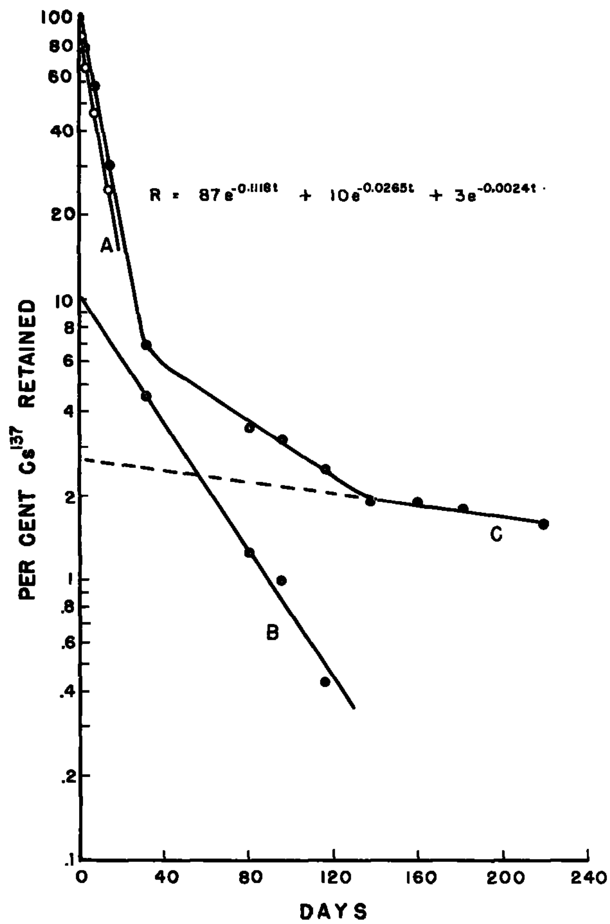

FIGURE 6.—Retention of Cs^{137} by croaker skin, showing separation of a typical composite curve into three rate functions.

relatively high concentration after 219 days. The composite retention curve was resolved into two rate functions with $t_{1/2}$'s of 34.8 and 94.7 days, representing 35 and 61 percent of the amount of Cs^{137} in muscle at zero time. The sum of both components was only 96 percent leaving a deficit of 4 percent which probably was masked by individual variation in samples. The retention of Cs^{137} by rat muscle was expressed as a 2-component curve with $t_{1/2}$'s of 8 and 16 days, representing 55 and 45 percent of the Cs^{137} at zero time (Ballou and Thompson, 1958).

Gonads accumulated Cs^{137} for 7 days before reaching a maximum concentration, which was considerably higher than that of skin and muscle. Although elimination of Cs^{137} was fairly rapid, the concentration remained higher than that of skin and muscle at the end of the experiment.

The retention data were expressed as a composite curve consisting of two rate functions which were extremely different from each other. The first component had a $t_{½}$ of 13.4 days, representing 86 percent of the Cs^{137} at zero time. The second component had a $t_{½}$ of 911.0 days, representing only 3 percent of the Cs^{137} at zero time. The sum of both components indicated a deficit of 11 percent which denoted either a third rate function not detectable from the data or a masking effect by variation. During the summer months it was noted that the gonads of both males and females discharged ripe sex products. Differences in retention between males and females were not evident from the data. Retention of Cs^{137} by rat ovaries was considerably different from croaker gonads. Ballou and Thompson (1958) reported a 3-component curve with $t_{½}$'s of 1.5, 7, and 17 days.

The concentration of Cs^{137} in liver at zero time was much higher than that of the other tissues. However, elimination from liver occurred at a rapid rate, resulting in a lower concentration than that of gonad and muscle after 219 days. The retention curve consisted of four rate functions with $t_{½}$'s of 0.7, 4.2, 24.0 and infinite days. The individual components represented 61, 37, 2, and 0.4 percent of the Cs^{137} at zero time. Ballou and Thompson (1958) reported the retention curve for Cs^{137} in rat liver as having three components with $t_{½}$'s of 2, 7, and 16 days, representing 69, 19, and 12 percent of the Cs^{137} at zero time.

DISCUSSION

In the present experiments an attempt has been made to reproduce conditions that occur in the natural environment. This approach was used especially in the long-term accumulation experiment with flounder and in both retention experiments.

Accumulation of Cs^{137} by flounder was followed through a temperature range which conformed to the gradual change from winter to spring temperatures in the local estuary. Although the reduction of food at certain times may have produced less than optimum conditions, it is conceivable that fish in their natural environment also tolerate periods of inadequate food supply. The fact that flounder had a higher concentration factor during the period in which they did not increase in weight than during the period in which they did increase may be contrary to what might be expected. However, if Cs is not essential for growth, the amount accumulated would not be proportional, necessarily, to the rate of weight increase.

According to the present results and published reports, Cs concentration factors for most fishes range approximately from 10 to 20, depending upon growth rate, water temperature, and other conditions. Young spot (*Leiostomus xanthurus*) had a concentration factor of 12 for the whole-body, 17 for viscera, and 23 for muscle (George H. Rees, U.S. Bureau of Commercial Fisheries, Beaufort, N.C.; unpublished data). Krumholz and others (1957) gave an approximate factor of 10 for soft tissues of marine vertebrates. Pendleton and Hanson (1958) reported concentration factors of 9,500 and 3,000 for muscle of sunfish (*Lepomis gibbosus*) and carp (*Cyprinus carpio*) in an aquatic community. These factors were based on the amount of Cs^{137} in the water after it had become stabilized at 5 percent of its original concentration, 95 percent having been removed in 50 hours by the ecosystem, including inanimate surfaces. If the same data on sunfish muscle were related to the initial Cs^{137} concentration of the water, they would yield a factor of 8+ which is in closer agreement with the present data.

Accumulation of Cs^{137} from sea water and from ingested material has been followed independently in the present investigation. In certain situations in the marine environment both of these pathways might be utilized simultaneously. In other situations, fish might absorb radioactivity mostly from food due to differences in migratory patterns between fish and their prey. In noncontaminated water, the rate of accumulation of radioactive Cs by fish depends upon the nature of the contaminated food ingested. For example, Pendleton and Hanson (1958) reported higher Cs^{137} concentration factors for carnivorous vertebrates than for omnivores. Fish feeding entirely on phytoplankton might be expected to have even lower concentration factors than omnivorous fish. This is based on data indicating that nine species of algae had concentration factors ranging from 1.2 for *Nitzschia closterium* to 3.1 for *Nannochloris atomus* (Boroughs and others, 1957).

The whole-body Cs^{137} retention curve of flounder consisted of two rate functions with $t_{1/2}$ values of 5.3 and 36.9 days. These are considerably lower rates than those found for clams and oysters, both of which had component $t_{1/2}$'s of 3 and 12 days (T. J. Price, unpublished data). It is pointed out that the muscle to organ ratio of fish is large compared to that of clams and oysters, which may account for the longer $t_{1/2}$ of Cs^{137} in flounder. Richmond (1958) expressed the retention of Cs^{134} in mice, rats, monkeys, dogs, and man as multiple rate function curves. None of the $t_{1/2}$ components for mice or rats exceeded 14 days. The component rate function of monkeys and dogs was more nearly similar to those of flounder, the $t_{1/2}$ values being 3, 23, and 40.5 days for monkeys and 1.1, 27, and 43.5 days for dogs.

The Cs^{134} retention curve for man consisted of two rate functions having $t_{1/2}$ values of 3 and 143 days. McNeill and Green (1959) gave the retention of Cs^{137} in man as a single rate function with an effective half-life of about 115 days. It is likely that the retention curve for flounder might have included a third rate function if it had been possible to continue the experiment. Also it is likely that the long accumulation period prior to the retention experiment might have influenced the characteristics of the retention curve by enabling a greater portion of the Cs^{137} to be concentrated in muscle. This is suggested by the slow rates of accumulation and loss by croaker muscle as compared to the other tissues.

Croaker muscle, with the lowest Cs^{137} concentration at zero time, retained the highest concentration after 219 days of all tissues tested. This was due to the relatively long $t_{1/2}$'s of 34.8 and 94.7 days, both of which were substantial percentages (35 and 61 percent) of the Cs^{137} at zero time. This is significant since muscle represents the greatest mass of tissue. A croaker prepared for the frying pan (less entrails, head, scales, and fins) represents approximately 53 percent of its original body weight; about 5 percent of this is bone, leaving 48 percent edible muscle and skin.

Liver, in contrast to muscle, had an extremely high Cs^{137} concentration at zero time, but 61 percent of this amount had a $t_{1/2}$ of 0.7 day, and 37 percent had a $t_{1/2}$ of 4.3 days. Consequently, the concentration was very low at 219 days.

Although the 911-day $t_{1/2}$ component of gonad and the infinite $t_{1/2}$ component of liver may seem unusually long, there is no indication that they would have remained unchanged with the arrival of summer temperatures. If observations were begun during the winter instead of the summer, one might expect component rate functions somewhat different from those obtained. Therefore, the present values should not be interpreted as fixed values, since they might be influenced by changes in temperature, salinity, food availability, and other factors in the environment.

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SUMMARY

A series of laboratory experiments were performed in which accumulation and retention of cesium^{137} by marine fishes were followed. In order to simulate conditions occurring in a marine environment which might control the availability of the radionuclide, Cs^{137} was administered orally to fish in some experiments while in others the fish were kept in sea water containing known amounts of the radionuclide.

1. Postlarval summer flounder (*Paralichthys dentatus*) concentrated 9 to 11 times the amount of Cs^{137} in sea water during a period of 91 days. The rate of accumulation per unit weight decreased during periods in which the flounder gained weight rapidly. On the other hand, when the flounder did not significantly gain weight, the rate of accumulation increased. This was attributed to the disparity between rate of accumulation and rate of weight increase.

2. Atlantic croaker (*Micropogon undulatus*) concentrated Cs^{137} in heart, liver, and spleen by a factor of 9 times the amount in sea water after 29 days. Muscle accumulated the radionuclide at a slower but more uniform rate with a concentration factor of 4.5.

3. Orally administered Cs^{137} was rapidly absorbed from the digestive tract of croaker with only 10.8 percent of the dose remaining after 24 hours.

4. Maximum concentrations of Cs^{137} occurred in all tissues of croaker, except muscle, within 24 hours following oral administration.

5. Tissue distribution of Cs^{137} was similar in croaker (*Micropogon undulatus*), bluefish (*Pomatomus saltatrix*), and little tuna (*Euthynnus alleteratus*) 24 hours following oral administration, with highest tissue concentrations in the following order: heart, liver, spleen, kidney, gills, gonad, muscle, skin+scales, blood, and bone.

6. Whole-body retention of Cs^{137} by postlarval flounder was expressed as two rate functions with biological half-lives ($t_{½}$'s) of 5.3 and 36.9 days representing 34 and 66 percent of the Cs^{137} at zero time.

7. Composite Cs^{137} retention curves of croaker tissue were resolved into multiple rate functions as follows:

Skin—Three rate functions with $t_{½}$'s of 6.2, 26.2, and 290.0 days representing 87, 10, and 3 percent of the amount of Cs^{137} at zero time.

Muscle—Two rate functions with $t_{½}$'s of 34.8 and 94.7 days, representing 35 and 61 percent of the amount of Cs^{137} at zero time.

Liver—Four rate functions with $t_{½}$'s of 0.7, 4.2, 24.1 and infinity representing 61, 37, 2, and 0.4 percent of the amount of Cs^{137} at zero time.

Gonad—Two rate functions with $t_{½}$'s of 13.4 and 911.0 days representing 86 and 3 percent of the amount of Cs^{137} at zero time.

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