Report Series in Radiochemistry 2/1972

The occurrence of ^{137}Cs in the biosphere evaluated with environmental and metabolic studies

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To be presented, with the permission of the Section of Mathematics and Natural Sciences of the Philosophical Faculty of the University of Helsinki, for public criticism in Auditorium XII on June 20th, 1972, at 12 o´clock noon.

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Unioninkatu 35 • 00100 Helsinki 10 • Finland

ISBN 951–45–0013–X

PRINT OY HELSINKI 1972

P R E F A C E

The present study was carried out in the Department of Radiochemistry, University of Helsinki, during 1962-1970.

I am greatly indebted to Professor Jorma K. Miettinen, head of the Department of Radiochemistry and my teacher, for his encouragement, advice and the constant interest shown in my work. The theme of my study was also his suggestion.

I also gratefully acknowledge the pleasant and highly valued cooperation of my colleagues, Mr. Seppo Kolehmainen, Ph. D., and Mrs Tua Rahola, M. Sc.

I wish to thank Mrs Anja Nykänen for translating the text into English and Mr Michael Wilson, Ph. D., for checking the language.

This investigation has been financially supported foremostly by the Finnish Atomic Energy Commission and the U. S. Atomic Energy Commission (AT-30-1-3446). Additional support has also been received for parts of the study from the Niilo Helander Foundation, the Finnish Academy of Science, and the Finnish Cultural Foundation, whom I also wish to thank hereby.

Helsinki, May 1972

Erkki Häsänen

THE PURPOSE OF THE INVESTIGATION AND THE PUBLICATIONS CONNECTED WITH IT

This work forms a part of the fall-out studies carried out in the Department of Radiochemistry, University of Helsinki. Its main emphasis has been on the -spectrometric determination of the ^{137}Cs-levels and changes herein in different environmental samples and in man after the second nuclear testing period in 1961-1962.

Special attention has been paid to the aquatic foodchains of ^{137}Cs, to the foodchain reindeer-lichen-man, and to the biological half-life of ^{137}Cs in man and in certain fish species.

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1. INTRODUCTION

1.1. Production of ^{137}Cs in nuclear explosions

Most of the radioactive nuclides released by nuclear weapons in the global fallout are produced through the process of fission. Certain heavy nuclei, such as those of ^{235}U and ^{239}Pu, disintegrate into two lighter nuclei. These are generally unstable and undergo further radioactive decay.

All fissionable material is not used up in the explosion and therefore such material will also be found in the radioactive fallout released.

The free neutrons produced in excess during fission activate the elements in the material of the bomb and also those in the environment surrounding the explosion. Nuclides produced in this manner are thus found in the radioactive debris of a nuclear explosion.

The main part of nuclear testing has been carried out in the atmosphere. The fallout therefore consists mostly of various fission nuclides. About 200 fission products are formed ranging in mass from about 70 to 170 a.m.u. and in periodic number from 28 to 65. The primary products formed are radioactive and decay with half-lives ranging from fractions of a millisecond to decades.

The fission reaction results in the formation of a large number of decay chains; as examples, the chains for mass numbers 90 and 137 are given below.[1] These chains yield two long half-life nuclides which are the most important from the radiation risk point of view.

Chain 90:

1.6 sec ^{90}Br <

→ 15 % 3.2 min ^{89}Kr + neutron

→ 85 % 32 sec ^{90}Kr → 2.6 min ^{90}Rb → 28 y ^{90}Sr → 64 h ^{90}Y → stable Zr

Chain 137:

24.4 sec ^{137}Cs <

→ 4 % stable ^{136}Xe + neutron

→ 96 % 3.9 min ^{137}Xe → 30 y ^{137}Cs < (→ 92 % 2.57 min ^{137m}Ba; → 8 % stable ^{137}Ba)

Both of these chains have in common the property that their fission yield is high (5-6 %) and that the products formed have long half-lives and closely resemble some biologically important elements; ^{90}Sr in the chain 90 acts chemically in a manner similar to calcium and is accumulated in the bones of animals and man through food-chains, whilst ^{137}Cs in chain 137 and resembling potassium, accumulates in soft tissues, mostly in muscles.

The greater part of fallout studies have concentrated on elucidating the radiation risk to man from these two long half-life nuclides. This means attempting to establish their transport mechanisms after nuclear explosion, their accumulation in man through various food-chains and their metabolism in man.

This study deals with these questions in relation to ^{137}Cs.

1.2. Transport of ^{137}Cs into the biosphere

Weapon detonations, equivalent in energy release to several megatons or more of high explosive, carry their fission products into the stratosphere where they are widely dispersed due to stratospheric diffusion and mixing. This material returns slowly to earth and is referred to as stratospheric fallout. Stratospheric fallout has made the greatest contribution to long-range or worldwide contamination, since over 90 % of all fission products produced by nuclear weapon tests have been from weapons with yields greater than on megaton.

The United States, the Soviet Union, and to a lesser extent Great Britain, France and The People's Republic of China, have all used nuclear testing in the development of nuclear weapons. The main part of this testing was carried out from 1957 to 1958, and from 1961 to 1962.

By the end of the year 1958 the fission production of the tests was about 90 megatons which corresponds to about 14 megacuries of ^{137}Cs. It is estimated that about 9 megacuries of this reached the stratosphere. About 70 % of the fission production originated from the tests carried out by the USA and Great Britain and the remaining 30 % from those carried out by the USSR.

There was no nuclear testing between December 1958 and August 1961.

During the second nuclear testing period (September 1961 - December 1962) the fission production in the atmospheric tests was about 100 megatons; 6 megatons being produced by the USA and 94 megatons by the USSR. An amount equivalent to 95 megatons of fission products, corresponding to 15 megacuries of ^{137}Cs, is believed to have been injected into the stratosphere during this period.[2]

In 1962 the USA, USSR and Great Britain ceased atmospheric testing.

From the atmospheric nuclear testing carried out by France and The People's Republic of China during the latter part of the 1960's, about 1.5 megacuries of ^{137}Cs is estimated to have reached the stratosphere and then been deposited as global fallout.

From 1963 to 1966, when no considerable amounts of fission products were released into the atmosphere, the ^{137}Cs fallout further decreased with a half-life of approx. 1 year. By the year 1967 the level of ^{137}Cs-contamination had fallen to that which existed before the beginning of the second test period in the year 1960. The annual fallout since 1967 has remained about the same or increased slightly due to the testing by China and France.[3]

The levels of the ^{137}Cs-fallout during 1958 to 1970 are presented in Fig. 1. The amount of the global ^{137}Cs-fallout was, in 1970, about 20 megacuries. This value is 20 % less than was estimated to have reached the stratosphere. The discrepancy is due, in part, to the fact that the estimates of one megaton fission produced and corresponding to a given amount of ^{137}Cs, vary (0.14-0.18 megacuries), and that there is no exact knowledge of the ^{137}Cs-level in the short-range fallout.

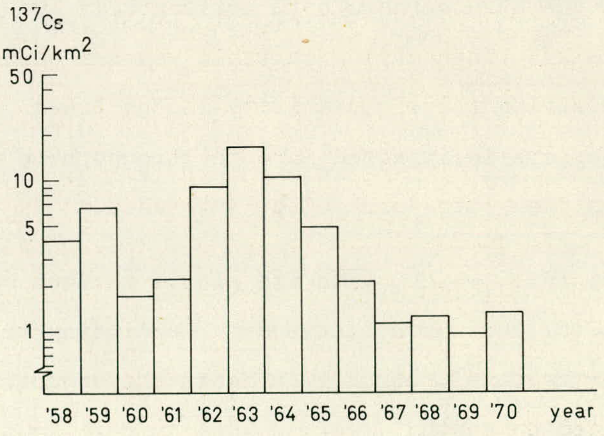


Fig. 1. Annual ^{137}Cs deposition in northen hemisphere (0-80° N) during 1958-1970.

It has been observed that the amount of fallout depends on the latitude in such a way that there is a clear maximum between the 40th and 45th latitudes in the northern hemisphere, whilst the fallout in the southern hemisphere is only about 1/5 of this. This results from the fact that most tests have been carried out in the northern hemisphere.[4]

Apart from being dependent upon the latitude, the level of fallout also varies with the seasons, being greatest in the spring, from April to May, and smallest in November.

The large geographic and seasonal variation in fallout levels in the northern hemisphere seem to be due to several factors, the most important of which probably are:

- the so called stratospheric jet in the Arctic which disintegrates during February - March, strongly mixing the stratosphere both horizontally and vertically. Then during suitable weather conditions in the spring the radioactivity in the lower stratosphere is injected into the troposphere between the 30th and 60th latitudes,[5,6]
- the rainfall, which, with its global maximum between the 40th and 50th latitudes (excluding the equator regions), strongly affects the amount deposited on earth.[7]

The mean residence time of ^{137}Cs in the stratosphere is estimated to be about a year and in the troposphere about a month.

The main part of the ^{137}Cs-fallout comes down with rain.

Along the same latitude the level of ^{137}Cs has been observed to be almost directly proportional to the amount of rainfall. 80 to 90 % of the ^{137}Cs fallout is water soluble.

The accumulated ^{137}Cs deposited on earth has been calculated on the basis of ^{90}Sr-analyses of the soil because the latter element has been investigated considerably more covering wider areas. It is known that the ratio $^{137}Cs/^{90}Sr$ in rain water, as well as in soil, is approximately constant, the average value being 1.6.[8]

In the northern hemisphere the cumulative deposition of ^{137}Cs on average was in the latter part of 1965 67 mCi/km^2. The corresponding fallout in Finland in the same period has been estimated to be 75 mCi/km^2.[9]

1.3. Occurrence of ^{137}Cs in the biosphere and the risk to man

After reaching the ground along with the rain, ^{137}Cs is very effectively bound by the soil or absorbed by plants through their outer surfaces. From plants ^{137}Cs is further transported, either directly or in the process of being eaten by animals, into man, the end point of the foodchain.[10]

A part of the ^{137}Cs that has reached water courses and seas is carried through various food chains into fish and further into man.

Most of the ^{137}Cs found in terrestrial plants comes down with the rain and is absorbed directly into plants through their outer surfaces, mainly through leaves. The potassium content of plants has also been noted to have an effect on the ^{137}Cs level therein; when the K-content increases, the ^{137}Cs-content decreases.

Plants, such as various lichens and mosses, which take their nutrients from rain water, contain between ten to a hundred times more ^{137}Cs than other terrestrial plants. These plants have a strong ion exchange capacity and are able to hold, in addition to nutrients, the nuclides that are transported in the rain water.

The ^{137}Cs-fallout in water courses is taken up by fish both directly through their gills and also through various foodchains. The contribution made by direct absorption from water is, however, slight. The ^{137}Cs-content of fish is foremostly determined by the ^{137}Cs-content of their food.

As with aquatic plants, the ^{137}Cs-level of aquatic organisms is determined in the first place by the K-content of the water; the ^{137}Cs-level of the organisms being, by and large, inversely proportional to the K-content of the water. In the sea, due to its high electrolyte and low ^{137}Cs-content, the ^{137}Cs-level in the fish is an order lower than in the fresh-watercourses.

The terrestrial animals obtain their ^{137}Cs from food. It is absorbed rapidly and almost completely from the alimentary canal. That which is excreted is mostly in urine (about 90 %).

The rate of excretion varies in different species according to the size of the animal. With increase in size, the rate of excretion in mammals generally decreases.[11] The ^{137}Cs-level in animals is foremostly determined by the ^{137}Cs-content of their food. The ^{137}Cs-level in the lichen eating reindeer and caribou, and in the wolverine and wolf preying on them, is higher by many factors of ten than that of other terrestrial animals.

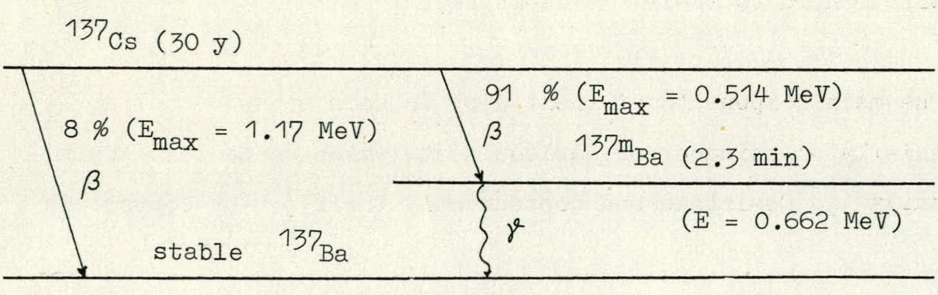
Man obtains most of his ^{137}Cs from milk, meat and grain products. Taking the human population as a whole, the reindeer and caribou breeders in the Arctic, the Lapps in Northern Europe and the Alaskan Eskimoes, are in a special position with regard to their ^{137}Cs-intake.

The main components of their diet in some seasons consist chiefly of reindeer or caribou meat, which means that their daily ^{137}Cs-intake and consequently their ^{137}Cs-content is several factors of ten higher than that of the population in general.

On an individual basis, apart from diet, the ^{137}Cs-level in humans is affected by the differences in the biological half-life of ^{137}Cs. On average this value is, in man, 100 ± 50 days. The biological half-life in children is clearly shorter than in adults, shorter in women than in men, increases with age and decreases during pregnancy.[13] A great many of the studies on ^{137}Cs are connected in one way or another with the evaluation of the radiation risk of this nuclide to the human population. It is estimated that by the year 2000 the nuclear tests carried out up to the end of 1962 will have caused to the population in the Northern hemisphere an increase of 2 - 3 % in the natural whole-body radiation burden. This natural radiation burden is composed mostly of ^{40}K and ^{14}C in the body, by the uranium and thorium in the soil, and by cosmic radiation.

1.4. Analyses of ^{137}Cs

^{137}Cs decays with a half-life of 30 years emitting both γ- and β-radiation.



^{137}Cs can be analysed either γ-spectrometrically or by β-counting.

The direct γ-spectrometric method can be used to determine the ^{137}Cs-levels in biological samples or in man (whole-body counting). These samples generally do not contain, in addition to ^{137}Cs, any other γ-nuclides apart from ^{40}K.

Samples which have high levels of other fission nuclides (for instance, plant samples that have been freshly contaminated by fallout) have to be decomposed before analysis either by ashing at about 400° C or by wet ashing. ^{137}Cs is then separated chemically and the sample content determined either γ-spectrometrically or by β-counting.[12]

The γ-spectrometric system consists usually of a background-shielded detector, a NaI(Tl) - crystal and a multichannel pulse height analyser. For β-counting a β-counter provided with an anti-coincidence shield and a thin window is used.

The efficiency of the NaI - detector in the γ-spectrometric determinations is of the order of 10 % and in whole-body counting of 0.1 - 0.5 %. In both cases the efficiency is highly dependent on the size of the detector used.

When the ^{137}Cs-content of the sample is very low (e.g. in water samples), β-counting is suitable because it is 2 to 3 times more efficient and the background is between ten to a hundred times smaller than in γ-spectrometric determinations. When the γ-activity of the sample is relatively high, a Ge(Li)-detector of good resolution and low efficiency can be used.

2. ANALYTICAL METHODS USED - A BRIEF SUMMARY

2.1. γ-spectrometric determination of ^{137}Cs directly from the sample

2.1.1. Sample counting

The γ-spectrometric system consisted of a 5" x 3" NaI(Tl) - crystal (Harshaw), a high voltage supply (IDL Unit type 532/D), and a 512-channel pulse height analyser (Finnish Cable 1 - 500).

As read-out units, a printer (Friden), X - Y analog reader (Houston EHR 931 M) and a paper punch (Creed 25 MK4), were used.

To eliminate the background, a lead shield measuring 48 x 27 x 27 cm on the inside, was used (Fig. 2). The outer layer consisted of 12 cm lead, followed by 1 mm of cadmium and 0.5 mm of copper as the innermost layer.

The counting has generally been carried out by placing the sample in a covered plastic container of the same diameter as the crystal and

45 mm in height. This type of container has been calibrated for use in determining ^{137}Cs and potassium and for some other nuclides.

For ^{137}Cs calibration an IAEA absolute standard was used, and for potassium calibration potassium chloride (Merck, p.a.). For calibration of the fission nuclides ^{54}Mn, ^{106}Ru + ^{106}Rh an IAEA absolute standard was used. The efficiency of the system for ^{125}Sb was calculated on the basis of this nuclide's decay scheme.

Table 1 gives a summary of the calibration results.

Table 1. The efficiency of the sample counting system for different nuclides and the contribution of each nuclide in the energy range of the others (as a percentage of the net counts of the photopeak).

Nuclide	Energy range MeV	Efficiency	Correction in the ^{137}Cs-range	^{54}Mn-range	^{106}Ru-Rh-range	^{125}Sb range
^{40}K	1.36-1.56	8.7 cpm/gK	19 %	19 %	22 %	22 %
^{54}Mn	0.78-0.90	156 cpm/nCi	14 %		13 %	13 %
^{137}Cs	0.60-0.72	156 cpm/nCi			7 %	14 %
^{106}Ru+ ^{106}Rh	0.48-0.54	24 cpm/nCi	43 %	10 %		21 %
^{125}Sb	0.40-0.46	81 cpm/nCi	60 %		17 %	

Since in some cases the sample volume has been smaller than the volume of the container (450 cm^3), calibration has also been carried out for other volumes and the volume correction coefficient K_v (Fig. 3) calculated.

Calibration was carried out using water solutions, i.e. of density 1 g/cm^3. The density of the samples measure has generally been less than 1, usually 0.5 - 0.7 g/cm^3. A density correction coefficient K_ϱ , shown in Fig. 4, was therefore calculated.

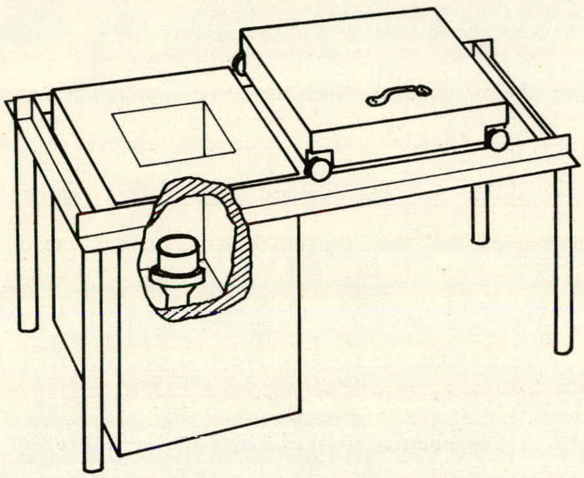


Fig. 2. Background shield of the sample counting system.

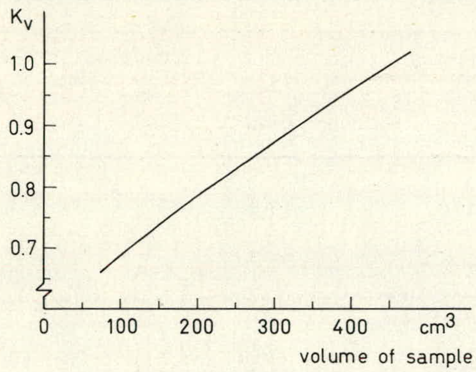


Fig. 3. Volume correction coefficient (K_v).

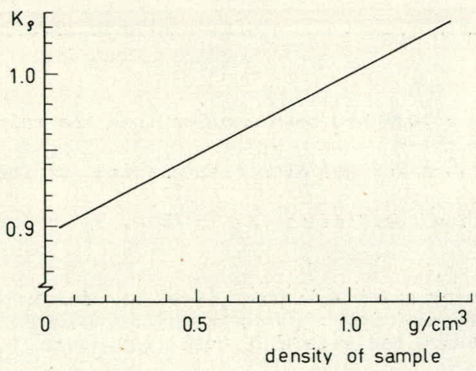


Fig. 4. Density correction coefficient (K_ϱ).

The coefficient was determined empirically using homogeneous, ^{137}Cs-containing plant material, packed to various densities.

If the sample contains no γ-nuclides other than ^{40}K, the ^{137}Cs-level can be calculated from the following equation:

$$x = \frac{S_{Cs-137} \cdot K_v \cdot K_\varrho}{e_{Cs-137} \cdot t \cdot w} \text{ nCi/kg}$$

where

S_{Cs-137} = number of counts in the ^{137}Cs-region, when the background and the counts due to ^{40}K have been subtracted;

K_v = volume correction coefficient;

K_ϱ = density correction coefficient;

e_{Cs-137} = efficiency of the system for ^{137}Cs (cpm/nCi);

t = time of counting (min);

w = weight of sample (kg).

In cases where the sample contained other fission nuclides besides ^{137}Cs, corrections were made for this in calculating the results (Table 1).

2.1.2. Whole-body counting

Equipment and detectors similar to those used in sample counting were used in whole-body counting. However, the background shielding and the geometry used were different.

The mobile whole-body counting system was accommodated in a closed van (Hanomag Kurier). It was equipped with two dressing rooms for those being counted, and a sliding frame-work for the crystal which was shielded with walls consisting of lead tiles. The detector was surrounded by between 4 to 8 cm of lead. Innermost in the enclosure was a 1 mm copper plate. The structure of the counting enclosure is shown in Fig. 5.

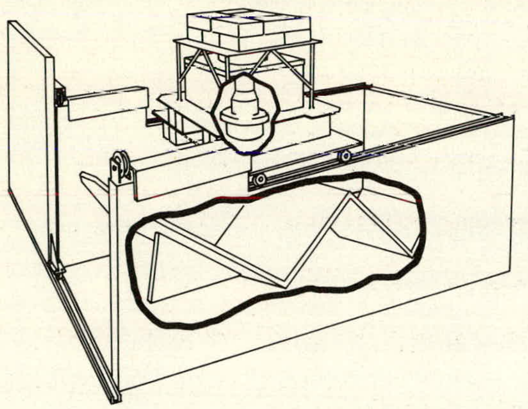


Fig. 5. Background shield of the mobile whole-body counting system.

The temperature in the van was maintained constant, ($20 \pm 2\ ^{\circ}C$) even in field conditions in winter, by a thermostatically controlled heating system and good insulation of the van.

The permanent whole-body counting system was located in an iron room and the equipment and geometry (the so called 1-detector-chair-geometry) were similar to those in the van. The inside measurements of the background shield were 180 x 180 x 120 cm. The wall was composed of 14 cm iron, 3 mm lead and 0.5 mm copper. In addition there was a 4 to 8 cm thick lead shield as in the mobile system. This counting laboratory was airconditioned so that the temperature and humidity were maintained at a constant level. The incoming air and the internal circulating air was filtered through electrostatic filters.

In the determination of whole-body counting results the equipment was calibrated for both ^{137}Cs and potassium. To calibrate the equipment, a phantom of plastic containers and test persons were used.

In phantom determinations the phantom was filled with a solution of known concentration of ^{137}Cs (IAEA absolute standard) and potassium (Merck, p.a. KC1). The solution wighed 70 kg.

To calibrate for ^{137}Cs with control persons, three persons were given a known amount of ^{137}Cs (IAEA absolute standard) and they were then counted during the following three days. Their excretion for this period was collected and its ^{137}Cs-content counted. On the basis of these results the efficiency of the system for ^{137}Cs was calculated for a person weighing 70 kg.

The following correction coefficient for the weight (w) variable could then be applied to the results obtained from counting different test persons:[14]

$$\frac{1}{1 + 0.004\ (70 - w)}$$

The calibration with the test persons gave an efficiency 5 % greater than that for phantoms. Since it is probable that the difference was due to the difference in geometry between the phantoms and the persons tested, a value of 1.05 x the efficiency in phantom calibration was used in the potassium determinations.

The reliability of the K-efficiency was controlled later by calibrating with four test persons who were given ^{42}K, together with a ^{42}K phantom, and with a phantom of natural potassium.

In the K-calibration with test persons the efficiency of the counting system was within the counting statistics of the value obtained in phantom calibration multiplied by the factor 1.05.

In whole-body counting the ^{137}Cs-content was calculated using the equation:

$$x = \frac{S_{Cs-137}}{e_{Cs-137} \cdot t} \cdot \frac{1}{1 + 0.004\,(70 - w)}$$

where

S_{Cs-137} = number of counts in the ^{137}Cs-region, when the background and the counts due to ^{40}K have been subtracted;

e_{Cs-137} = efficiency of the system for ^{137}Cs (cpm/nCi);

t = time of counting (min);

w = weight of person (kg).

2.1.3. Characteristics of the counting system

A summary of the characteristics of the sample and whole-body counting systems is given in Table 2.

Table 2. Characteristics of the counting systems in ^{137}Cs- and K-determinations. The detector was a 5" x 3" NaI(Tl)-crystal.

Counting system	Resolution % ^{137}Cs	Resolution % ^{40}K	Integration background 0.1 - 1.8 MeV, cpm	Background ^{137}Cs region, cpm	Background ^{40}K region, cpm	Efficiency cpm/nCi ^{137}Cs	Efficiency cpm/gK	Contribution by ^{40}K in energy range of ^{137}Cs, % of photopeak area
Sample counting	9.0	6.4	512	48	25	156.1	8.71	19
Whole-body counting, van	10.8	7.1	1 027	73	39	2.76	0.180	30
Whole-body counting, permanent	10.8	7.1	547	48	24	2.76	0.180	30

2.1.4. Precision of the ^{137}Cs analyses in direct γ-spectrometric determinations

The main sources of erros in direct γ-spectrometric determinations were: the statistical error in counting, the inaccuracy of the standard used in calibration, the errors in the values of the volume and density correction coefficients due to the inaccuracy in the volume determination of the sample, the inaccuracy of the counting system (as shown by the deviation of the results in repeatedly counting the same sample, even after correction for the statistical error) and the error due to the presence of other γ-nuclides in the sample.

The effect of other fission nuclides in the sample, which, in some cases (e.g. plants), may be the greatest source of error and even eliminate the possibility of using direct -spectrometric analysis, has not been considered here. In most of the samples studied, only natural potassium containing ^{40}K (in addition to ^{137}Cs) has been noted. The potassium increases the ^{137}Cs background by 5 - 10 % in analyses and therefore increases to some extent the statistical error of the determination.

The statistical error in counting is affected by the activity of the sample, the background radiation and the length of the counting interval. A standard deviation (σ), calculated by taking these factors into account, is usually given for the results obtained.

The percentage standard deviation is given by the equation:

$$\sigma (\%) = \frac{100}{S} \qquad \frac{B}{t_b} \qquad \frac{B+S}{t_s}$$

where

B = background radiation in the energy range of a given nuclide (cpm);

S = activity of the sample in the same energy range (cpm);

t_b = counting interval of background (min);

t_s = counting interval of sample (min).

In this work the statistical error of counting (σ_1) has varied, depending on the ^{137}Cs-content of the sample, from 0.5 to 20 %. On average it has been in the order of 2 - 3 %, both in sample counting and in whole-body counting.

The accuracy of the activity of the solution used in the ^{137}Cs-calibrations was given by the manufacturer as $\pm$ 2 %. In the calibration itself (3 parallel determinations) the error was $\pm$ 0.5 %. This means that the accuracy of the calibration was almost the same as the accuracy of the activity of the calibration solution or $\pm$ 2 % (σ_2).

The error in volume determinations caused an error in the estimates of the volume correction factor and the density correction factor. In all, this error was at most $\pm$ 2 % (σ_3).

To test how reliably the results could be repeated with the systems used, counting of so-called standard preparations was carried out at 2 to 3 week intervals both in the sample counting and whole-body counting systems. It was shown that the repeatability with both systems was about $\pm$ 1 % (σ_4).

Since these errors are independent of each other, the total error caused by them, assuming the statistical error to be ± 2 %, is ± 3.6 % (σ) and $2\sigma = \pm 7.2$ %.

This means that at the 95 % confidence level the error in the results is smaller than ± 7 %, provided that the statistical error of the counting is less than ± 2 %.

An indication of the reliability of the results was also obtained through participation in a control test carried out by seven laboratories whereby the ^{137}Cs-, ^{90}Sr-, ^{210}Pb-, and ^{226}Ra-contents of four different samples were determined.[15]

The results given in Table 3. were obtained for the ^{137}Cs content of the sample (i.e. the greater the statistical error of counting), the greater is the distribution of the results.

The clear deviation in the results for horse-tail may have been caused by the fairly large levels of other γ-nuclides in the sample in proportion to ^{137}Cs.

The precision of the whole-body counting system was tested by repeatedly counting the same person within a short time in 1962, both in Helsinki and in Lund (Radiofysiska Institutionen), and in 1963 in Vienna (IAEA Whole-body Counting Laboratory) and in Helsinki (Table 4.).

As can be seen the control counts agree approximately to within ± 2 %.

Table 3. Results of the ^{137}Cs-analyses of the control samples

Sample	Laboratory number	^{137}Cs nCi/kg (dry weight)
Reindeer meat	3	64.0 ± 0.6
	4	65.1 ± 0.6
	5	64.1 ± 0.3
Reindeer bone	3	3.7 ± 0.1
	4	3.9 ± 0.3
	5	5.6 ± 0.2
Reindeer lichen	3	10.3 ± 0.3
	4	10.1 ± 0.3
	5	13.6 ± 0.1
	9	14.3
Horse-tail	1	3.5 ± 0.4
	4	1.0 ± 0.1

Table 4. Results of the control whole-body counting

Location	Date	nCi ^{137}Cs
Helsinki	23.10.1962	80.2 ± 2.5
Lund	28.10.1962	78.4 ± 2.0
Vienna	29.10.1963	37.5 ± 1.3
Helsinki	2.11.1963	36.1 ± 1.4

To summarise, it may therefore be stated that for those activities which the samples generally represent in fallout studies, the accuracy of direct γ-spectrometric ^{137}Cs-analyses is of the order of 5 - 10 %.

2.2. γ-spectrometric determination of ^{137}Cs after chemical separation

The chemical separation of ^{137}Cs was carried out using a method based on coprecipitation with fresh ammonium molybdophosphate precipitate, as given in detail in publication VII.

2.3. Determination of ^{137}Cs by β-counting after chemical separation

The HASL standard method was used to determine the ^{137}Cs-content of water samples.[16] The activity of the preparations was measured with an IDL anticoincidence β-counter of 1-2 cpm background.

3. SUMMARY OF THE RESULTS

3.1. ^{137}Cs-content of plants in Finland during 1962-1965 (V, VII, IX)

Most of the plant samples represent the years 1962-1963, but some samples were also from the years 1964-1965.

The ^{137}Cs-level in annual terrestrial plants was in 1962 about 25 nCi/kg (dry weight), and in 1963 about 5 nCi/kg.

There were no great differences in the ^{137}Cs-levels between different species. The local variation within a species was also slight.

The ^{137}Cs-activity level in aquatic and waterside plants was on the average higher and the local variation much greater than in the terrestrial plants. For instance, the ^{137}Cs-level in horse-tail varied in 1963 from between 3-30 nCi/kg (dry weight). The ^{137}Cs-activity level in lakes rich in nutrients was clearly lower than that in lakes low in nutrients. Horse-tail (Equisetum fluviatile) seemed to be a suitable "indicator plant" for estimating the general ^{137}Cs-level of the biota in inland waters.

The ^{137}Cs-level of the perennial lichen (Cladonia alpestris) which takes its nutrients directly from the air, was an order higher than that in the annual, terrestrial plants. In 1962 the level was about 20 nCi/kg (dry weight), in 1963 about 40 nCi/kg and in 1964-1965 about 60 nCi/kg. The increase observed from 1962 to 1963 coincides with a fallout deposit of about 9 mCi/km^2 of ^{137}Cs, which is the same as the average annual ^{137}Cs fallout measured in Finland (based on the ^{90}Sr analyses of the fallout).

3.2. ^{137}Cs-content of fish and plankton in Finland during 1962-1965 (I, II, V, IX)

The fish samples analyzed have been from the years 1962-1965 and the plankton samples from 1964 to 1965.

The ^{137}Cs-content of the fish samples varied steeply depending on the electrolyte level of the water. In lakes low in nutrients the ^{137}Cs-level in fish was 5 to 10 times higher than that in lakes rich in nutrients.

The correlation between the ^{137}Cs-level in the fish and the K-content of the water was especially clear.

In 1964 the average ^{137}Cs-level in fish in eutrophic lakes was 1.3 nCi/kg (fresh weight) and that in plankton about 0.1 nCi/1; in oligotrophic lakes the corresponding values were 4.9 nCi/kg (fresh weight) and about 0.4 nCi/1, respectively.

The ^{137}Cs-level in fish in oligotrophic lakes increased all through the period investigated (1962-1965), but a maximum was reached in eutrophic lakes during 1964.

The K-content of the water exerted the strongest influence on the ^{137}Cs-content in fish in different lakes, and the differences in the biological half-lives of ^{137}Cs were decisive in producing the differences in levels between various fish species.

3.3. ^{137}Cs in the Finnish population during 1961-1966 (II, VI)

The main emphasis of the studies of ^{137}Cs-levels in man in

Finland has been on the Lapps, because their ^{137}Cs-content and its radiation risk to them has been observed to be exceptionally high compared to the rest of the population.

By the so-called random sampling method, 10 %, or 250 persons, of the Finnish Lapp population were selected for the Lapp studies. Those chosen lived in the three northernmost communes in Finland: in Enontekiö, Inari and Utsjoki. Vocationally they could be divided into three groups: reindeer-herders, reindeer-herding fishers, and those of other occupations.

The first counting was carried out after the mobile whole-body counting system had been constructed in the spring of 1962. 172 persons (112 men and 60 women) volunteered, that is, over 80 of those who had received the invitation.

The counting was repeated using smaller groups the next autumn and in the springs of 1963, 1964, 1965 and 1966.

The results showed that the ^{137}Cs-levels in women were about half of the levels in the men in corresponding vocational groups, and that there was a clear difference in the activity levels between different vocational groups. A dietary investigation revealed that the differences between the vocational groups were mostly due to the difference in the amount of reindeer meat in their diets, and the difference between the sexes due to the fact that women consume 50 % less food than men.

Further, it was observed that during summer the ^{137}Cs-level decreased by about 40 % from the spring maximum. The decrease was on one hand due to the smaller proportion of reindeer meat in the diet in summer and on the other to its decreased activity level when the reindeer in summer change their fodder from lichens to annual plants.

The nuclear testing in 1961-1962 caused a continuous increase in the ^{137}Cs-levels in Lapps up to the year 1965 when the most active group, the Inari reindeer herders, reached an average ^{137}Cs-level of 1560 nCi, which is half of the highest permissible ^{137}Cs-level for a restricted population group. The individual maximum of 2660 nCi was measured in the spring of the previous year and it is about 9 % of the highest permissible level for an individual in a radiological occupation group (the corresponding ICRP maximum permissible levels are 3 μCi and 30 μCi).

In the spring of 1966 the average ^{137}Cs-level in Lapps was about 15 % less than the maximum recorded the year before.

The observed changes in the ^{137}Cs-levels in Lapps have also been discernible in the earlier links of the food chain, the reindeer and lichen.

The ^{137}Cs-levels in Southern Finns, and changes in it, have been followed since November 1961, when the levels in a control group of 5 men and 6 women were measured in

Sweden. The levels in the same group were measured a year later in the mobile whole-body counting system of the Department of Radiochemistry.

Within a year the ^{137}Cs-level had increased three-fold in women and two-fold in men.

For further study, two new and larger control groups were selected at the beginning of 1963; 24 girl students from a domestic science college and 25 privates from an infantry batallion. In both cases the diet was checked by the interview method and it was considered to be representative of a typical diet in Southern Finland.

During 1963 both groups were measured in May, August, October and December. In addition, the women were also measured in March 1964.

The ^{137}Cs-levels in both groups remained almost constant in the beginning of 1963 but increased by almost 40 % between the period from May to August. The reason was that the cattle were then let out to pasture which caused a steep increase in the ^{137}Cs-levels in milk and meat (the main contributors to the ^{137}Cs-intake) in the beginning of July. Before the increase the average ^{137}Cs-intake for women was 156 pCi/person/day and for men 252 pCi/person/day. The corresponding levels after the increase were 240 pCi/person/day and 400 pCi/person/day, respectively.

From August until the end of the year the ^{137}Cs-level of both control groups increased by a further 15-20 %.

In the spring 1963 the ^{137}Cs-levels in southern Finns were 1/40th of those in the Inari reindeer-herders.

3.4. The biological half-life of ^{137}Cs in man (II, X)

In 1962 in connection with the calibration of the whole-body counting system three women (average age 35 years) and three men (average age 40 years) were given orally a known dose of ^{137}Cs. Their ^{137}Cs-levels were followed for about half a year and the following biological half-lives were recorded: women 42, 53, 56 days (average 50 days) and men 53, 81, 93 (average 77 days).

The sudden elevation in the ^{137}Cs-intake of the southern Finnish control groups made it possible to determine the average biological half-life of ^{137}Cs in both groups on the basis of the daily intake of ^{137}Cs and whole-body counting. The $BT_{1/2}$-value obtained for women was 60 days and for men 64 days.

In 1969 the biological half-life of ^{137}Cs in ten men (average age 29 years) was investigated by administering a single oral dose. In this investigation the biological half-lives varied between 54 - 104 days, the average being 84 days.

The biological half-life of ^{137}Cs was found to be significantly correlated with the amount of ^{137}Cs excreted in urine during the first 24 hours after a single oral dose ($r = 0.83$, $p < 0.001$) and with the amount of sodium excreted in urine ($r = -0.81$, $p < 0.01$).

3.5. The biological half-life of ^{137}Cs in some fish species (VI, VIII)

Differences in the ^{137}Cs-levels in fish were observed to exist not only between different lakes but also between the species in a lake. The differences between lakes were observed to be caused by the varying K-content of the water. To establish the factors causing the differences in ^{137}Cs-levels between the species, the biological half-life of ^{137}Cs was investigated. The biological half-life of ^{137}Cs was studied in five fish species by giving them ^{137}Cs orally either in a gelatin solution or in a tight gelatin capsule and by measuring the ^{137}Cs in them in the mobile whole-body counting system, at first daily, and then later on at one week intervals.

The $BT_{1/2}$-values observed (slow component, measured at 15° C) were: perch about 200 days, roach 57 days (3-year-olds), and 100 days (11-year-olds). At the same temperature the $BT_{1/2}$ -value in rainbow trout varied between 20-80 days depending on age. In 1-year-old trout when the temperature of the water fell from 20° to between $7-8^{\circ}$ C, the half-life rose from 20 to 36 days.

Five-year-old Crucian carp were found to have a biological half-life of 10 days at 20° C.

A fall in temperature of ten degrees increased the biological half-life of ^{137}Cs by about two-fold in all the fish species investigated.

If the ^{137}Cs-content of fish and its biological half-life is known, it is feasible to estimate the daily ^{137}Cs-intake of fish in natural conditions.

On the basis of this study, the differences in the ^{137}Cs-levels between species are caused by the different biological half-lives of ^{137}Cs in such species.

4. OCCURRENCE OF ^{137}Cs IN THE BIOSPHERE AS EVALUATED BY VARIOUS STUDIES CARRIED OUT IN FINLAND IN THE 1960's

The results presented above form part of the studies on the occurrence of ^{137}Cs undertaken in Finland in the 1960's. The studies presented in this dissertation have been further pursued by Professor Miettinen's group in the Helsinki University Department of Radiochemistry.[17-20]

The Institute of Radiation Physics, as the supervisory authority, has carried out large scale studies on the magnitude of the ^{137}Cs-fallout, the ^{137}Cs-levels in milk, and the ^{137}Cs-level in southern Finns.[21]

On the basis of these studies, Figs 6 - 7 depict the changes in ^{137}Cs-levels in different parts of the biosphere of Finland in the 1960's.

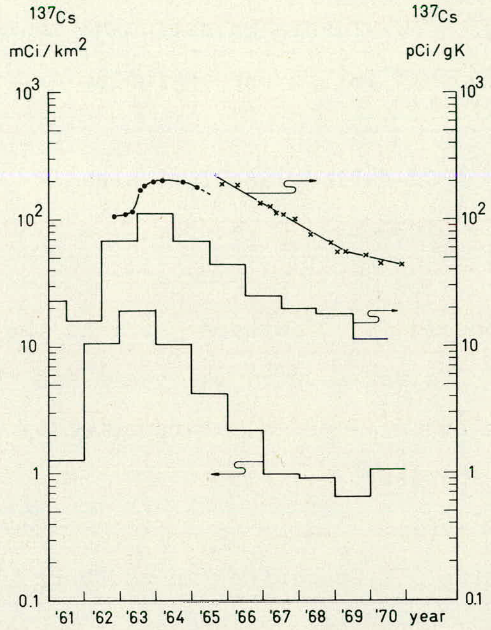


Fig. 6. Average annual ^{137}Cs deposition in Finland (mCi/km^2). ^{137}Cs-levels in milk in Southern Finland (pCi/gK). The ^{137}Cs-level in the population in Southern Finland (pCi/gK) (the control group at the Department of Radiochemistry ....; at the Institute of Radiation Physics xxx).

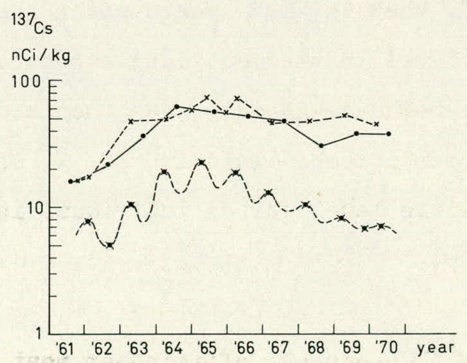


Fig. 7. ^{137}Cs-levels in lichen (• •), reindeer meat (xx), and in the Inari reindeer-herders (⁎⁎).

After the second nuclear testing period ending in December 1962, in Finland a maximum in the ^{137}Cs-fallout was reached in July of 1963; at the same time this maximum was observed in the ^{137}Cs-levels in milk, and in man a good half-year later, that is, in the beginning of 1964.

The amount of ^{137}Cs-fallout declined steadily during 1963-1967 with a half-life of about 10 months.

In the milk produced in Southern Finland the corresponding half-life of ^{137}Cs was about 1.4 years and that in the southern Finns about 2 years, as reported by the Institute of Radiation Physics.

The maximum in the ^{137}Cs-content in southern Finns observed a year and a half after the cessation of nuclear testing, represent about one per cent of the level permitted by the ICRP for individuals in a restricted population group.

The maximum in the ^{137}Cs-level in Lapps was reached in the spring of 1965, that is 2.5 years after the end of nuclear testing. The level in the most active population group, the male Inari reindeer herders, was then about 10 nCi/gK or 1.5 μCi per person. This is 50 % of the ICRP maximum permissible level for an individual in a restricted population group.

In 1965 the ^{137}Cs-content of reindeer meat, the main source of ^{137}Cs in the Lapps, was about 70 nCi ^{137}Cs/kg (fresh weight). The level in the main component of the reindeer fodder, lichen, was during the corresponding time about 60 nCi/kg (dry weight). In the first two phases of the foodchain lichen-reindeer-man the ^{137}Cs-level has decreased at a rate of $T_{1/2}$ 10 years, whilst the activity level in man has declined, after the maximum was reached, at a faster rate; the $T_{1/2}$ value being 4 years in 1965-1968.

The changes in way of life and food consumption of the Lapps in the middle 1960's probably have had an effect on this rapid decline. A dietary investigation in 1971 revealed that the amount of reindeer meat in the diet has become smaller and, apart from this, its use has become more evenly distributed throughout the year since deepfreezers have become more common.[22]

The leveling out is seen also in the whole-body values for spring and autumn. In 1962, in the summer, there was a 40 % decrease in the ^{137}Cs-level in the Inari reindeer-herders whilst the corresponding decrease in 1969 was only 15 %.

Since 1968 the ^{137}Cs-level in Lapps has remained almost constant, and this is probably due to the atmospheric nuclear testing by The Peoples Republic of China in the latter half of the 1960's.

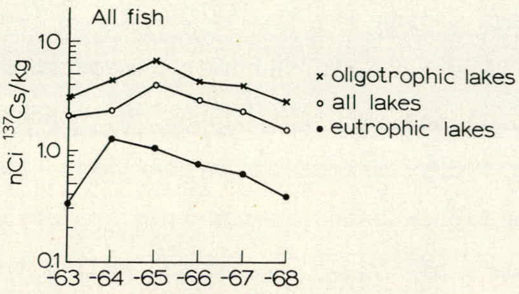


Fig. 8. ^{137}Cs-levels in fish in Finland (nCi/kg fresh weight).

The maximum in the ^{137}Cs-level in fish was reached in 1964 in eutrophic lakes, and in 1965 in oligotrophic lakes (Fig. 8). The average ^{137}Cs-level in Finnish lakes was in 1965 about 4 nCi/kg (fresh weight).[23]

After reaching the maximum, the ^{137}Cs-level in fish has decreased (in 1965 - 1968) with a $T_{1/2}$-value of 2 - 4 years, depending on the fish species and lake type.

5. THE RADIATION RISK OF ^{137}Cs TO THE POPULATION OF FINLAND

The annual radiation dose caused by ^{137}Cs is, for an adult, about 8 mrem per nanocurie per kilogram of weight.

When the ^{137}Cs-content of the population was at its maximum in 1964 - 1965, the dose received by the Lapp reindeer-herders was about 100 mrem/year, and the corresponding value for the southern Finns about 3 mrem/year (Fig. 9).

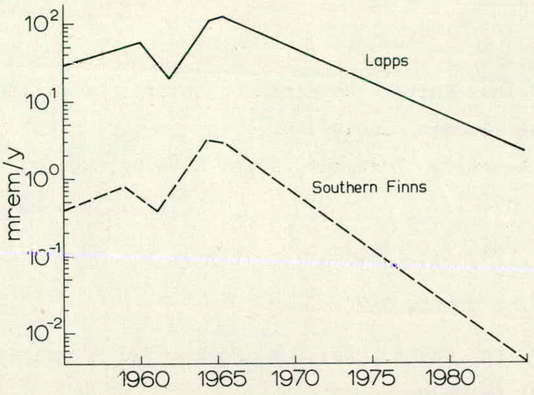


Fig. 9. Radiation dose from whole-body ^{137}Cs to southern Finns (---), and to reindeer-herding Lapps (——) at Inari, Finland, between 1955 - 1985.

The radiation dose from ^{137}Cs received by the present generation during 1955 - 1985 has been estimated to be for the Lapp reindeer-herders about 1 rem and for the southern Finns about 25 mrem.[24]

The natural radiation dose of the Lapps is about 5 rem/30 years and that of the southern Finns about 2 rem/30 years. Therefore, in considering the radiation dose from ^{137}Cs, in the Lapps there is an increase of about 20 % and in the southern Finns an increase of about 1 % in the natural radiation burden.

Additional radiation burdens of this magnitude are considered to be so slight from both the health and genetical standpoints that their effect cannot be statistically established.

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Cæsium-137 Content of Fresh-water Fish in Finland

INVESTIGATIONS of the diets of the Finnish Lapps[1,2] have revealed that fish is the second important source of radiocæsium for several Lapp groups. Unexpectedly, high radiocæsium values, especially in pike, were obtained in the first analyses of Lapland fish[2]. Therefore it seems important to carry out substantial research on the hydrospheric chains of fall-out nuclides both in Lapland and other parts of Finland. In the following the results of our fish analyses up to the present time are briefly reported. These include analyses of cæsium-137 and potassium in 23 samples of fish from the Finnish Lapland and a number of samples from 2 lakes in southern Finland.

The fish were caught during the period 1961–63. The main part of the samples, 21 in number, were taken from Lake Inari (28° E., 69° N.), one sample from the Kemi river (24° E., 66° N.) and one from the Näkkälä river (24° E., 69° N.). The samples taken for comparison are from southern Finland, from the Pyhäjärvi (23° E., 61° N.) and Näsijärvi (23° E., 62° N.) lakes, and were caught in the spring of 1963. In addition, we have analysed 3 fish samples from the Varanger fjord on the Arctic Ocean (30° E., 70° N.), caught in May 1962. At the fishing place the fish were weighed and their lengths were measured. After this the entrails and heads were removed and the fish were soaked in formalin so as to preserve them. Later a scale sample was taken for age determination. Also, the 'teeth' of the gill arches of the whitefish were counted in order to determine the subspecies. The fresh weight of the samples was usually 1·5–2 kg. The fish were dried at 100°–110° C. They were ground and their activity was measured in a cylindrical plastic container, the diameter of which was the same as that of the crystal on which it was placed. The volume of the container was 0·5 l.

The 512-channel pulse-height analyser was made by the Finnish Cable Works, and Harshaw's 3 in. × 5 in. sodium iodide crystal was used. The calibration of the system for the determinations of cæsium-137 was made with a Radiochemical Centre standard solution *CDR* 4 2/11/60. For the potassium calibration Merck's potassium chloride was used. In the cæsium-137 range (0·60–0·72 MeV) the sensitivity was 13·9 c.p.m./nc. and in the potassium range (1·38–1·56 MeV) 7·38 c.p.m./g potassium. The corresponding backgrounds were in the cæsium-137 range 2·90 c.p.m. and in the potassium range 1·49 c.p.m. The potassium correction in the cæsium-137

Table 1. CÆSIUM-137 BURDEN OF LAKE FISH IN LAPLAND

When caught (month–year)	Where caught	Fish species	Age (year)	Cæsium-137 (nc./kg fresh weight)	Potassium (g/kg fresh weight)	Cæsium-137 nc./g potassium
				2σ	2σ	
Sept. '61	Kemijoki	Pike (*Esox lucius*)		3·90 ± 0·05	3·7 ± 0·4	0·95
Jan. '62	Inari	Pike		2·78 ± 0·05	2·9 ± 0·4	0·96
,, ,,	,,	Whitefish (*Coregonus lavaretus*)		0·64 ± 0·03	1·2 ± 0·3	0·53
May '62	,,	Perch (*Perca fluviatilis*)		2·41 ± 0·05	2·9 ± 0·4	0·83
,, ,,	,,	Whitefish		0·83 ± 0·03	3·0 ± 0·4	0·28
July '62	,,	Brook trout (*Salmo salvelinus salvelinus*)	6	3·22 ± 0·05	3·4 ± 0·4	0·94
,, ,,	,,	Perch	10	2·81 ± 0·05	3·0 ± 0·4	0·93
,,	,,	Lake trout (*Salmo trutta lacustris*)	6	2·27 ± 0·04	3·6 ± 0·4	0·63
,, ,,	,,	Pike	8	1·74 ± 0·07	3·5 ± 0·4	0·50
,, ,,	,,	Grayling (*Thymallus vulgaris*)	3	1·01 ± 0·04	4·0 ± 0·4	0·25
,, ,,	,,	Whitefish	6	0·95 ± 0·06	3·5 ± 0·4	0·27
,, ,,	Näkkälänjoki	Brown trout (*Salmo trutta fario*)	5	2·70 ± 0·05	4·6 ± 0.4	0·59
Sept. '62	Inari	Pike	4	5·90 ± 0·06	3·3 ± 0·4	1·79
,, ,,	,,	Lake trout	6	3·46 ± 0·05	3·2 ± 0·4	1·08
,, ,,	,,	Grayling	4	1·82 ± 0·04	4·3 ± 0·4	0·42
,, ,,	,,	Whitefish	4	1·11 ± 0·04	3·6 ± 0·4	0·31
Mar. '63	,,	Lake trout		4·65 ± 0·06	3·2 ± 0.4	1·45
,, ,,	,,	Arctic char (*Salmo salvelinus alpinus*)		4·65 ± 0·06	3·3 ± 0·4	1·41
,, ,,	,,	Brook trout		3·84 ± 0·05	2·6 ± 0·3	1·48
,, ,,	,,	Whitefish	8	1·56 ± 0·04	2·8 ± 0·4	0·56

Table 2. CÆSIUM-137 (NC./KG FRESH WEIGHT) IN THREE SUB-SPECIES OF WHITEFISH FROM LAKE INARI, JULY 1962

	Average no. of gill arch teeth (a) acc. to Järvi	(b) in sample	Average age (yr.)	Cæsium-137 (nc./kg)
Coregonus fera Jur.f. *inarensis* Järvi ('Jokisiika')	21·6	22·0	5	0·57
Coregonus wartmanni Bl.f. *borealis* Järvi ('Riika')	33·1	32·0	6	0·95
Coregonus holsatus Thien f. *inarensis* Järvi ('Lehtisiika')	24·0	24·3	7	1·34

range was 0·26 c.p.m./g potassium. The lead shield used for the reduction of the background count was 12 cm thick. The system was calibrated for the density 1·0 and the correction for the variation of the density was 3–4·5 per cent. Each sample was measured for 1 h and in the cæsium-137 determinations the value of 2σ varied as follows: When the cæsium-137 content was 0·1 nc./kg (fresh weight) $2\sigma = \pm$ 14 per cent and when the cæsium-137 content was 5·0 nc./kg (fresh weight) $2\sigma = \pm$ 1 per cent. In the potassium determination 2σ was about ± 6 per cent. The results of the measurements are presented in Table 1. The samples taken in January 1962 were analysed at Lund[2].

An examination of the Lapland samples reveals that the cæsium-137 content of various fish species vary rather much (0·6–6 nc./kg). If the samples are divided into two groups on the basis of their activity using 2 nc./kg as the dividing line it will be noted that the fish containing more than 2 nc./kg are fish of prey and that the low activity group includes only grayling and whitefish, which feed on insects, insect larvæ and plankton.

Several sub-species of whitefish are distinguished in Lake Inari, three species of which were analysed separately (Table 2). Considerable inconsistency prevails regarding the Latin names of these sub-species. Those used in Table 2 were given by Järvi[3]. For the *C. fera* Jur.f. *inarensis* Järvi the name *C. pidschian* Gmelin is also used. The samples were taken in July 1962.

The results show a tendency in the direction of diminishing activity when the feed changes from plankton to bottom animals. In general the activity of the whitefish unambiguously seems to have risen during the year 1962. An analysis of the activity of pike and trout also support this fact.

If the Lapland samples are compared with Arctic Ocean samples (Table 3) there is a clear difference between the cæsium-137 values. The activity of the Arctic Ocean samples is only about 1/20th of that of the Lapland samples. It also seems that the cæsium-137 values of the fish in southern Finland are somewhat lower than in Lapland. So far as the samples from southern Finland are concerned, however, comparison is difficult for the reason

Table 3. Cæsium-137 in Fish caught in the Arctic Ocean and Lakes in Southern Finland

When caught (month-year)	Where caught	Fish species	Age (year)	Cæsium-137 (nc./kg fresh weight)	Potassium (g/kg fresh weight)	Cæsium-137 nc./g potassium
				2σ	2σ	
May '62	Arctic Ocean Varanger Fjord	Salmon (*Salmo salar*)		0·15 ± 0·02	4·4 ± 0·4	0·034
,, ,,	,,	Halibut (*Hippoglossus vulgaris*)		0·07 ± 0·02	3·8 ± 0·4	0·0053
,, ,,	,,	Cod (*Gadus callarias*)		0·02 ± 0·02	3·8 ± 0·4	0·0018
Nov. 62	Näsijärvi	Bream (*Abramis brama*)	15	0·54 ± 0·03	3·8 ± 0·4	0·14
Feb. '63	,,	Perch-pike (*Lucioperca sandra*)	4	1·86 ± 0·04	3·1 ± 0·4	0·60
,, ,,	,,	Burbot (*Lota vulgaris*)		1·82 ± 0·04	3·2 ± 0·4	0·57
,, ,,	,,	Pike		1·80 ± 0·04	2·8 ± 0·4	0·64
,, ,,	,,	Whitefish	5	1·40 ± 0·04	3·2 ± 0·4	0·44
,, ,,	Pyhäjärvi	Roach (*Leuciscus rutilus*)	8	0·25 ± 0·02	2·7 ± 0·4	0·093
,, ,,	,,	Pike	4	0·24 ± 0·02	3·3 ± 0·4	0·070
,, ,,	,,	Ide (*Leuciceus idus*)	6	0·18 ± 0·02	2·7 ± 0·4	0·067
,, ,,	,,	Silver bream (*Abramis farenus*)	7	0·17 ± 0·02	3·0 ± 0·4	0·057
,, ,,	,,	Burbot		0·17 ± 0·02	2·0 ± 0·3	0·085
,, ,,	,,	Bream	8	0·10 ± 0·02	2·4 ± 0·3	0·073

that the Näsijärvi and Pyhäjärvi samples represent quite different levels of activity. For example, if the cæsium-137 activities of fish of the same species, burbot and pike, are compared in the two lakes, 8–10 times higher activities are observed in the Näsijärvi samples. These two lakes are reported to represent two different lake types, Näsijärvi being a humus type of lake, Pyhäjärvi a low-humus 'rich' lake. Humic acids are weak cation exchangers and some limnologists consider them to represent an important dietary item for the zooplankton. It thus seems that the fish got the main part of their radiocæsium through their food intake even though a smaller part may come directly from the water through the mechanism in the gills which regulates the salt balance. Also, it seems plausible that the high cæsium-137 contents found in the fish of prey in the two lakes of humus-type is due to a food chain humus—zooplankton—small fish—big fish.

Age determinations were made of 22 fish samples dealt with here. No clear correlation between the age and the cæsium-137 content of fish of the same species could be observed. Fresh-water fish have been analysed since 1961 for radionuclides in Sweden too. with results of a similar type[4].

The results presented here will form a basis for the planning of more comprehensive studies of the cæsium-137 content of fish in which attempts will be made to clarify the enrichment chains of cæsium-137 from the water through plankton and bottom animals to the fish.

Limnological advice by Dr. Reino Ryhänen and aid in acquiring some of the fish samples by Mr. Jorma Toivonen are gratefully acknowledged. The age determinations were made by Mr. Lauri Peippo.

This investigation was supported by a grant from the Finnish Atomic Energy Commission and by scholarships to one of us (E. H.) from the Suomalainen Tiedeakatemia and the Niilo Helander Foundation.

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Reprint from

"ASSESSMENT OF RADIOACTIVITY IN MAN"

Vol. II

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1964

THE BODY BURDEN OF CAESIUM-137 IN PEOPLE OF SOUTHERN FINLAND 1961-1963

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Abstract — Résumé — Аннотация — Resumen

BODY BURDEN OF CAESIUM-137 IN PEOPLE OF SOUTHERN FINLAND 1961-1963. In connection with the investigations of the caesium-137 body burden of Finnish Lapps several measurements of smaller groups of people living in Southern Finland were carried out.

In November 1961 eleven Helsinki inhabitants, five men and six women, 15 to 54 yr old, were counted for caesium-137 and potassium in Stockholm. None of these persons were laboratory workers, two were schoolboys.. They were apparently healthy. Their diet was studied by the interview method. Ten of these people were counted again in the mobile whole-body counter of the Radiochemical Department of the University of Helsinki one year later. The average body burden of caesium-137 in men (5, average age 29) had increased from 8.4 nc in November 1961 to 18.4 nc in November 1962, in women (5, average age 34) from 2.9 nc to 8.7 nc. Potassium contents were the same within 2% (men 140 g, women 100 g).

For more detailed studies larger control groups were selected at the beginning of 1963 and counted four times, in February, May, August and October. For the group of men 25 privates of an infantry battalion (age 19, average weight 65 kg), for women 24 girl students of a household school (age 22, average weight 60 kg) were selected. In both cases the diet could be checked in detail and could be considered to be an average Finnish diet. In addition, the individual food consumption of each subject was studied by interview with the aid of weighed samples. Caesium-137 contents of both diets were determined for the time periods between the measurements.

In both groups the caesium-137 content remained about constant (men, 17.5 nc; women, 11 nc) until the end of June, when the caesium-137 content of milk and meat was approximately doubled within about one week. At the end of August the body burden of caesium-137 had increased in both groups to about 40% above the spring level; in the middle of October the men's values had increased by 22%, the women's values by 14% of the August level. The determination of the biological half-time of caesium-137 from the dietary intake is discussed.

CHARGE CORPORELLE DE CÉSIUM 137 CHEZ LES HABITANTS DE LA FINLANDE MÉRIDIONALE EN 1961-1963. Dans le cadre des recherches sur la charge corporelle de césium 137 chez les Lapons de Finlande, il a été procédé à plusieurs dosages sur de petits échantillons de la population résidant dans le sud de la Finlande.

En novembre 1961, on a fait à Stockholm des dosages de césium 137 et de potassium sur onze habitants de Helsinki - cinq hommes et six femmes - âgés de 15 à 54 a. Neuf étaient des employés de laboratoire et deux des écoliers. Tous paraissaient être en bonne santé. On leur a demandé de donner oralement des renseignements sur leur régime alimentaire.

Un an plus tard, dix de ces onze sujets ont fait de nouveau l'objet de dosages au moyen de l'anthropogammamètre mobile du Département de radiochimie de l'Université de Helsinki. On a constaté qu'entre novembre 1961 et novembre 1962, la charge corporelle moyenne de césium 137 était passée chez les cinq hommes (âge moyen 29 a) de 8,4 à 18,4 nc et chez cinq femmes (âge moyen 34 a) de 2,9 à 8,7 nc. Les variations de la teneur en potassium ne dépassaient pas 2%; cette teneur était de 140 g chez les hommes et de 100 g chez les femmes.

Aux fins d'une étude plus poussée, on a choisi au début de 1963 des échantillons plus nombreux, qui ont fait l'objet de dosages à quatre reprises: en février, mai, août et octobre de cette année. L'un des échantillons était constitué par 25 fantassins d'un même bataillon (âge 19 a, poids moyen 65 kg) et l'autre par 24 étudiantes d'une école d'arts ménagers (âge 22 a, poids moyen 60 kg). Dans les deux cas, il a été possible de contrôler minutieusement le régime alimentaire qui pouvait être considéré comme normal pour des Finlandais. En outre, on a étudié, au moyen de portions de poids connu, la consommation individuelle des diverses denrées alimentaires, sur laquelle on a demandé à chacun des sujets de donner oralement des renseignements. On a déterminé quelle était la teneur en césium 137 des produits alimentaires consommés par chaque groupe pendant les intervalles entre les dosages.

Pour les deux groupes, la charge de césium 137 est demeurée sensiblement constante (hommes 17, 5 nc, femme 11 nc) jusqu'à fin juin; à partir de ce moment, la teneur du lait et de la viande en césium 137 a approximativement doublé en une huitaine de jours. A fin août, la charge corporelle de césium 137 avait augmenté, dans l'un comme dans l'autre échantillon, de 40% par rapport à ce qu'elle était au printemps; à la mi-octobre, on relevait chez les hommes une augmentation de 22% et chez les femmes une augmentation de 14% par rapport aux chiffres relevés en août.

La détermination de la période biologique du césium 137 d'après les quantités de produits alimentaires consommées fait l'objet de quelques observations.

СОДЕРЖАНИЕ ЦЕЗИЯ-137 В ОРГАНИЗМЕ У ЖИТЕЛЕЙ ЮЖНОЙ ФИНЛЯНДИИ В 1961 – 1963 гг. В связи с исследованиями содержания цезия-137 в организме у финских лопарей были проведены измерения у небольшой группы жителей южной Финляндии.

В ноябре 1961 года в Стокгольме у 9 служащих и 2 школьников Хельсинки (5 мужчин и 6 женщин в возрасте от 15 до 54 лет) было измерено содержание цезия-137 и калия в организме. Все были клинически здоровы. Характер диеты был установлен методом опроса. У 10 человек из этой группы измерение было проведено повторно с помощью передвижного счетчика для измерения радиоактивности всего организма на данном факультете Университета спустя год. Среднее содержание цезия-137 в организме у мужчин (5 человек, средний возраст 29 лет) повысилось с 8,4 ммккюри в ноябре 1961 года до 18,4 ммккюри в ноябре 1962 года; у женщин (5 человек, средний возраст 34 года) с 2,9 до 8,7 ммккюри. Содержание калия изменялось в пределах 2% (мужчины 140, женщины – 100 г).

Для более точных исследований в начале 1963 года были отобраны две контрольные группы, и измерения производились четыре раза: в феврале, мае, августе и октябре. Группа мужчин состаяла из 25 рядовых пехотного батальона (возраст 19 лет, средний вес 65 кг), группа женщин из 24 девушек-студенток (возраст 22 года, средний вес 60 кг). В обеих группах диета была тщательно проверена и расценивалась как обычная диета жителей Финляндии. Кроме того, индивидуальное потребление пищи у каждого обследуемого изучалось с помощью опроса и взвешивания образцов пищи. Содержание цезия-137 в диете обеих групп определяли в периоды между измерениями.

В обеих группах содержание цезия-137 оставалось почти постоянным (мужчины 17,5 ммккюри; женщины 11 ммккюри) до конца июня, после чего содержание цезия-137 в молоке и мясе увеличилось почти в два раза в течение одной недели. В конце августа содержание цезия-137 в организме увеличилось в обеих группах почти на 40% по отношению к весеннему уровню. В середине октября показатели у мужчин увеличились на 22% , а у женщин на 14% по отношению к августовскому уровню. Обсуждается определение периодов полувыведения цезия-137 на основании данных поглощения с пищей.

CARGA CORPORAL DE CESIO-137 EN CIERTOS GRUPOS DEMOGRÁFICOS DEL SUR DE FINLANDIA EN 1961-1963. Con motivo del estudio de la carga corporal de cesio-137 en los lapones de Finlandia se realizaron asimismo varias determinaciones en grupos demográficos más limitados residentes en el sur de Finlandia.

En noviembre de 1961 se sometió al recuento del cesio-137 y del potasio a un grupo de once habitantes de Helsinki (cinco hombres y seis mujeres, de edad comprendida entre 15 y 54 años). Nueve de ellos trabajaban en laboratorios y los dos restantes eran escolares. Todos gozaban aparentemente de buena salud. Para estudiar su régimen alimenticio, se recurrió al método de las entrevistas.

Un año más tarde se repitió el recuento de diez personas del grupo en el antropogammámetro móvil del Departamento de Radioquímica de la Universidad de Helsinki. La carga corporal media de cesio-137 en los cinco hombres (promedio de edades: 29 años) había aumentado de 8, 4 nc en noviembre de 1961 a 18, 4 nc en noviembre de 1962, mientras que en las cinco mujeres (promedio de edades: 34 años) de 2, 9 nc a 8, 7 nc. El contenido de potasio no acusó variaciones (dentro de un margen de 2%), manteniéndose en 140 g para los hombres y 100 g para las mujeres.

A fin de efectuar estudios más detallados, a principios de 1963 se eligieron grupos testigo más numerosos y se sometieron al recuento cuatro veces, a saber, en febrero, mayo, agosto y octubre, respectivamente. El grupo masculino estaba compuesto por 25 soldados de un batallón de infantería (edad: 19 años; peso medio: 65 kg); el femenino por 24 estudiantes de economía doméstica (edad: 22 años; peso medio: 60 kg). En ambos casos, el régimen alimenticio pudo comprobarse en detalle; resultó ser el típico de la población de Finlandia. Además, se estudió el consumo individual de alimentos de cada sujeto, mediante entrevistas y recurriendo a muestras de peso conocido. Se determinaron los contenidos de cesio-137 de los dos regímenes correspondientes a los intervalos entre las mediciones.

En ambos grupos, el contenido de cesio-137 permaneció casi constante (hombres: 17,5 nc; mujeres: 11 nc) hasta fin de junio, cuando la proporción de cesio-137 en la leche y la carne prácticamente se duplicó en un plazo de una semana. A fin de agosto, la carga corporal de cesio-137 había crecido casi 40% con respecto al valor registrado en la primavera; a mediados de octubre el contenido en los hombres había aumentado en un 22% y en las mujeres en un 14% con respecto a agosto. Los autores discuten los resultados de la determinación del semiperíodo biológico del cesio-137 absorbido con los alimentos.

1. SUBJECTS STUDIED

In connection with the investigations of the Cs^{137} body burden of Finnish Lapps (see the following paper) several measurements of smaller groups of people living in southern Finland were carried out.

The two first measurements were performed with eleven inhabitants of Helsinki, six women and five men, 15 to 54 yr old, who were counted for Cs^{137} and potassium in Stockholm in November 1961, and in Helsinki in November 1962. Nine of these persons were laboratory workers and two were schoolboys. They were apparently healthy and their diet and food consumption, which were checked by the interview method, were typical for city people and intellectual workers.

For more detailed studies larger "control groups" were selected at the beginning of 1963. Attempt was made to get these groups as homogeneous as possible regarding the age, diet, and physical activity. For the group of men 25 privates of an infantry battalion (age 19, average weight 65 kg), for that of women 24 girl students of a "houshold school" (a domestic science college) (age 22, average weight 60 kg), were selected. In both cases the diet was checked and could be considered to be an average Finnish diet. In addition, the individual food consumption of each female subject was determined by interviews with the aid of weighed samples. For the male subjects the study of individual diets was not possible, but their average food consumption could be determined from the food consumption records of the battalion. The Cs^{137} contents of all main food items were determined in each time period between the measurements in order to make possible calculations of the Cs^{137} intake.

2. WHOLE-BODY COUNTING

The second measurement of the smaller groups in November 1962 and the first measurement of the larger groups in February, 1963 were performed by the mobile counter (for a description of this counter and its calibration, see next paper), but the later measurements were performed in the iron room of this Department. This "room" has the same counting geometry and efficiency but a lower background than the mobile counter and it was calibrated in the same way as the latter. The calibrations of the two counters were cross-checked and the counting efficiency was checked periodically by phantom measurements. Intercalibration of our counters by "live" cross-countings with the whole-body counters of the International Atomic Energy Agency (Dr. R.A. Dudley) and Lund University (Dr. K. Lidén) proved that all these counters gave the same results within 4%.

One standard deviation of single measurements in the present study was 5 to 15% for Cs^{137}, 10% for potassium.

3. RESULTS OF WHOLE-BODY COUNTING

The results of the first two measurements are presented in Table I. As can be seen, the increase from November 1961 to November 1962 was about threefold in the female group and slightly more than twofold in the male group. This difference is partly due to the fact that in November 1961 the body burden of one of the male subjects was three times the average, due to elk-meat consumed, and increases the mean value of men in November 1961.

TABLE I

BODY BURDEN OF Cs^{137} OF HELSINKI SUBJECTS*

	Age	Weight	Height	(nc Cs^{137})		(gK)		(pc Cs^{137}/gK)	
	1962	1962	1962	1961	1962	1961	1962	1961	1962
Women: Average	34	60	163	2.9	8.7	99	97	29	90
Men: Average	29	77	177	8.4	18.4	139	139	59	132

* Subjects measured in November 1961. at AB Atomenergi, Stockholm
Same subjects re-measured in November 1962, at the University of Helsinki, 5 women and 5 men.

The results of the measurements of the larger groups, 20 to 25 subjects in each, are presented in Table II. As can be seen from this Table, the women's body burden of Cs^{137} (pc/g K) increased by 65% and the men's by 89% from February to December 1963. The potassium contents remained unchanged in both groups (women 1.6; men 2.2 g K/kg). The results of all measurements are summarized in Fig. 1.

4. Cs^{137} IN MILK, BEEF AND TOTAL DIET

The results of Cs^{137} measurements in milk by two laboratories are presented in Fig. 2. As can be seen, the level of Cs^{137} in Helsinki milk (one-day samples) was relatively constant (about 100 pc/l) until the beginning of July when it increased by about 60% within a short time (about one week). This higher level was then maintained until the end of the year.

The results of analyses of average monthly samples from two powdered milk factories, Somero and Nastola, were obtained from the Institute of

TABLE II

BODY BURDEN OF Cs^{137} IN PEOPLE OF SOUTHERN FINLAND FROM FEBRUARY 1963 TO MARCH 1964*

	Age (yr)	Weight (kg)	Height (cm)	Feb. 1963		May 1963		Aug. 1963		Oct. 1963		Dec 1963		March 1964	
				Cs^{137} (nc)	Cs^{137} (pc/gK)	Cs^{137} (nc)	Cs^{137} (pc/gK)	Cs^{137} (nc)	Cs^{137} (pc/gK)	Cs^{137} (nc)	Cs^{137} (pc/gK)	Cs^{137} (nc)	Cs^{137} (pc/gK)	Cs^{137} (nc)	Cs^{137} (pc/gK)
Women:															
Average	22	60	164	11.0	112	10.9	114	15.2	165	17.5	178	17.3	185	18.7	204
Min.				6.8	70	8.3	75	10.7	119	13.7	131	12.2	142	13.5	138
Max.				17.3	146	15.9	171	26.8	229	25.4	261	28.1	277	27.2	296
Men:															
Average	19	65	173	16.4	113	17.2	126	25.4	185	31.6	224	30.4	214		
Min.				10.4	73	13.1	91	20.5	137	25.2	175	21.8	150		
Max.				29.6	181	26.1	191	30.8	239	38.8	266	46.4	311		

* 24 Students of Järvenpää Household School and 25 Privates of Infantry Battalion

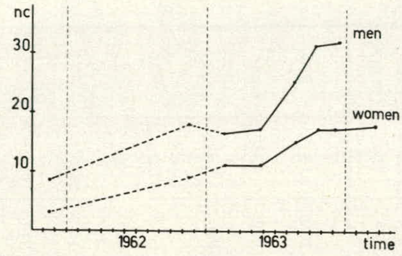

Fig. 1

Cs^{137} body contents of men and women from southern Finland from November, 1961 to March, 1964. In the two first measurements there were 5, in the later measurements 20 to 25 subjects in both groups.

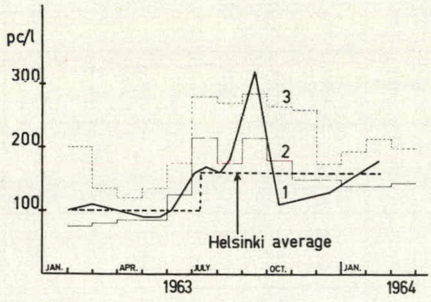

Fig. 2

Cs^{137} in milk in southern Finland from January, 1963 to March, 1964

1. One-day samples from Helsinki
2. Average monthly samples from the Somero area
3. Average monthly samples from the Nastola area

Radiation Physics [1]. The monthly mean values from the Somero area (23.5°E, 60.5°N) are on the same level but show a less sharp maximum than the one-day samples from Helsinki, but those from the Nastola area (26.7°E, 61°N) are essentially higher. The average Helsinki levels marked in Fig. 2 were used in this study.

The Cs^{137} content of beef, too, was constant (550 pc/kg fresh weight) until July when it increased by about 80% (to 1000 pc/kg fresh weight).

Calculations of the Cs^{137} content in the total diet showed that the intake of Cs^{137} through milk and beef was 70% (46 + 24%) in the female group. In the male group it was 72% (47 + 25%) of the total intake.

After the increase of the activity level in July the total intake of Cs^{137} by the women was 240 pc/d per subject (= 4 pc/kg body weight/d), that of the men 470 pc/d per subject (7.2 pc/kg d). However, the latter value is based on the battalion's food consumption lists and is uncorrected for losses in preparation and food left uneaten. Since these losses can be estimated to be about 15 to 25%, the food intake value for men may be as much as 25% too high. However, the error in the Cs^{137} intake is lower than this, about 15 ± 5%, since milk, the main source of Cs^{137} in the diet, is usually consumed nearly quantitatively.

5. BIOLOGICAL HALF-TIME OF Cs^{137}

The sharp increase in the dietary intake of Cs^{137} in July made possible calculations of the approximate half-time of this nuclide in women and men.

The change from the lower to the higher level of Cs^{137} intake was assumed to have taken place on 10 July. The body contents of Cs^{137} were assumed to have remained unchanged from May until this date. For the calculations, Cs^{137} values (nc/kg body weight) of only those subjects (18 women, 16 men) who had been subjected to every measurement, were used. These values with the calculated standard deviation and its confidence interval are presented in Table III.

The mathematical equation used in the calculation was based on the following assumptions:

From 10 July onwards the subjects had a constant daily intake, a, nc Cs^{137}. Simultaneously Cs^{137} was excreted from the body at a rate k, which is proportional to the body content A.

The change in the Cs^{137} body content is

$$dA = \frac{a}{w} \times dt - kA \times dt, \quad (1)$$

in which w = mean body weight in kg. The solution of Eq. (1) is

$$A = A_0 + \left(\frac{a}{wk} - A_0\right)(1 - e^{-kt}), \quad (2)$$

which gives the average Cs^{137} body content of the group at the time t. In Eq. (2) k is unknown and was determined for both groups by the "best fit" to the observed values.

For the female group the body content (nc/kg) is

$$A_{fem} = 0.309 - 0.129 \times e^{-0.0129\,t},$$

and for the male group

$$A_{male} = 0.527 - 0.257 \times e^{-0.0136\,t}.$$

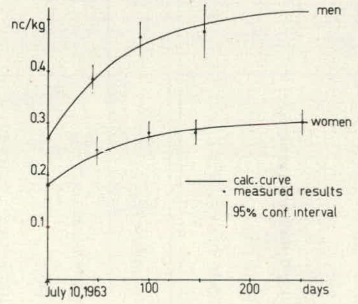

Fig. 3

Cs^{137} body content (nc/kg body weight) in control groups of 16 men (age 19) and 18 women (age 22). The same subjects in all measurements. For calculation of the theoretical curves, see text.

TABLE III

BODY BURDEN OF Cs^{137} (nc/kg) IN TWO CONTROL GROUPS FROM JULY 1963 TO MARCH 1964*

Women	10. 7. 1963	27. 8. 1963	17. 10. 1963	2. 12. 1963	15. 3. 1964
No. of measurements (n)	18	18	18	18	18
Mean ($\bar{x}$)	0. 180	0. 247	0. 282	0. 283	0. 304
σ of single measurement (s_x)	0. 040	0. 055	0. 045	0. 048	0. 055
σ of mean ($s_{\bar{x}}$)	0. 009	0. 013	0. 011	0. 011	0. 013
95% conf. interv. of $\bar{x}$	0. 160-0. 200	0. 220-0. 274	0. 259-0. 304	0. 259-0. 306	0. 276-0. 331
Men	**10. 7. 1963**	**22. 8. 1963**	**8. 10. 1963**	**11. 12. 1963**	
No. of measurements (n)	16	16	16	16	
Mean ($\bar{x}$)	0. 270	0. 385	0. 468	0. 479	
σ of single measurement (s_x)	0. 056	0. 050	0. 057	0. 096	
σ of mean ($s_{\bar{x}}$)	0. 014	0. 012	0. 014	0. 024	
95% conf. interv. of $\bar{x}$	0. 240-0. 300	0. 358-0. 411	0. 438-0. 496	0. 428-0. 530	

* 18 Students of Järvenpää Household School and 16 Privates of Infantry Battalion (same subjects in each measurement).

The theoretical curves are presented in Fig. 3, with the measured values and their 95% confidence limits indicated by bars.

The "apparent half-time" of the Cs^{137} uptake thus obtained is 51 d for the men and 54 d for the women.

We know, however, that about 10% of the daily Cs^{137} intake has a very high excretion rate with a half-time of about 1 d [2, 3]. If we take this into account and use Eq. (3) (for the derivation of this equation (see ref. [3]),

$$A = A_0 \times e^{-k_1 t} + \frac{(1-p)a}{wk_1}[1 - e^{-k_1 t}], \quad (3)$$

in which

k_1 = the slow biological fractional excretion rate of Cs^{137} d^{-1}

p = fraction of the daily intake being excreted at the fast excretion rate, nc.

we get for the long half-time components: 60 d for women and 55 d for men.

We also know (see section 4) that the men's Cs^{137} intake calculated from food consumption lists is estimated to be 15 ± 5% too high. When this correction is made we get 64 d for men. Thus, the half-times for the "slow component" obtained in this investigation are

women 60 ± 9 d,
men 64 ± 16 d.

The errors given include both those of the Cs^{137} intake values, which were considered to be ± 10% for women and ± 15% for men (nutritional chemist's estimate) and those of the average values of the Cs^{137} body burdens, which were ± 5% (68% conf. interv.) for both groups.

The above values are in excellent agreement with the value of 68 d obtained by Lidén and Naversten for nine Swedish Lapps ([3], p. 33) and with the values of 65 ± 10 d for large groups (33 women, 50 men) of Finnish Lapps [3]. They are also in satisfactory agreement with those obtained by us for six adult subjects from Helsinki, who took orally 300 to 400 nc Cs^{137} and were then measured periodically for six months in 1962. For these subjects the following half-times for the "slow component" were obtained: women (mean age 35): 56, 53 and 42, mean 50 d; men (mean age 40): 53, 81 and 93, mean 77 d.

The latter groups are too small to give statistically significant results, as biological half-times of Cs^{137} in individuals differ greatly. We have observed in the present study that the Cs^{137} body content in the steady state in one of two girls of the same age, weight and dietary Cs^{137}-intake may be 40% higher than in the other, and other authors have made similar observations (e.g. [4]). RUNDO [5] gives as the standard deviation ±35% for the biological half-time of Cs^{137} in man.

However, the present groups as well as those of the Finnish Lapps measured earlier [3] are large enough to give statistically significant results, and all the above half-times are shorter than most obtained outside Scandinavia (for a recent review see RUNDO [6]). Rundo, for instance, gives as the average for adults in England 105 d ± 35% [5]. HUYCKE and OBERHAUSEN from Landstuhl, Germany, give a mean half-time of 140 d for persons older than 22 yr [4]. Half-times longer than 80 d are definitely impossible for the large groups we have measured. Therefore, it seems that in the people of northern countries Cs^{137} has a shorter biological half-time than elsewhere. This may be due to differences in the diet.

ACKNOWLEDGEMENTS

We gratefully acknowledge a grant from the Finnish Atomic Energy Commission by which this investigation was made possible. We also wish to thank Miss Aili Jokelainen for the dietary data, Mr. O. Castren for Cs^{137} values of the monthly milk samples, Dr. Esko Kaila for aid in the mathematical calculations, and Mr. I. Ö. Anderson for the first whole-body measurements of the smaller control groups in Stockholm. We are much indebted to Mrs. A. Tare, Director of the Järvenpää Domestic Science College, and to Major General P. Somer, M. C., Surgeon General, Finnish Defence Forces, for aid given in selection of the large control groups.

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^{137}Cs LEVELS IN FISH OF DIFFERENT LIMNOLOGICAL TYPES OF LAKES IN FINLAND DURING 1963

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(*Received* 3 *September* 1965; *in revised form* 8 *November* 1965)

Abstract—The limnological characterization of twelve lakes and three rivers in different parts of Finland and ^{137}Cs analyses of several species of fish in these lakes and rivers were carried out. The lakes vary from oligotrophic (low-nutrient) lakes through dys-oligotrophic and dys-eutrophic to fully eutrophic (high-nutrient) lakes. Correspondingly, the conductivity varies from 11 to 79 mho units, the colour from 5 to 100 mg Pt/l., the $KMnO_4$ consumption from 8 to 144 mg/l., and the ^{137}Cs content in different fish species in more or less direct relationship with the diminishing conductivity, e.g. perch (*Perca fluviatilis*) 0.2–20 nc/kg, pike (*Esox lucius*) 0.15–16 nc/kg, roach (*Leuciscus rutilus*) 0.1–7.5 nc/kg fresh weight, the highest values being in the fish of oligotrophic lakes, which waters have a low electrolytic conductivity. Other factors affecting the ^{137}Cs content of the fish are its feeding habits and the general limnological character of the waters. The total β-activity of the water varies only slightly and this variation evidently is not an important cause of the differences found in the ^{137}Cs content of the fish.

In connection with the whole-body counting of the Finnish Lapps in 1961 it was observed that the ^{137}Cs content of the fresh water fish in Lapland was high. This led in 1962 to more extensive determinations of ^{137}Cs in fish.[1,2] In addition to those from Lapland, samples were collected for comparison from two neighbouring lakes in Southern Finland. Tenfold differences were observed in the ^{137}Cs contents of the same fish species. When it was established that these lakes were limnologically different types, this led to the systematic analysis of the ^{137}Cs contents of fish in different lake types and of the reasons for the observed differences in the activity levels. This investigation was begun in the spring of 1963 and it is still underway. In this paper results for the year 1963 are reported.

LIMNOLOGICAL CHARACTERIZATION OF THE FRESH WATERS INVESTIGATED

Lakes can be classified into two main types, eutrophic and oligotrophic. In the former the amount of nutrients is large and in the latter it is small. The abundance of nutrients in the water is dependent on the geology of the surroundings and the effects of civilization.

In addition to these main types there is, as a subgroup, the dystrophic type. Dystrophy is caused by brown humic acids emerging from swamps; they give the water a more or less brown colour. Dystrophy is usually connected with oligotrophy but it can exist also with eutrophy. In the first case the lake is called dys-oligotrophic and in the latter dys-eutrophic—or mixotrophic.

Oligotrophic, clear-watered lakes are mainly situated in rocky and sandy hill regions, in the Alps and in Lapland. The oligotrophy of some of the lakes in the Alps and in Southern Sweden is only apparent, since it is caused by an excessive calcium content and not by a lack of nutrients.

Eutrophy is the type of cultivated and fertile areas. Its main distribution area in Europe consists of Middle Europe, the Baltic countries, Denmark, Southern Sweden (Vettern and Stockholm as the northern border), the south-western and southern coastal regions of Finland, and it continues through the Carelian isthmus to the Onega lake. The main regions of different lake types in Finland are presented in Fig. 1.

Most of the lakes in Fenno-Scandia and in the other northern regions of the globe are characterized by dystrophy. This is a consequence of the abundance of swamps in these areas.

The fresh waters investigated are presented in Table 1 and their locations illustrated in Fig. 2. In Table 1 are listed the type, the location and the area of these fresh waters. The concept of a

Table 1. *Lakes and rivers under study*

Lake no.	Lake	The limnological lake type	Location Lat.	Long.	Area (Hectares)
1	Niemenjärvi	eutrophic, pelotr.	60 40′	26 00′	8
2	Kytäjärvi	dys-eutrophic, pelotr.	60 40′	24 40′	200
3	Mustalampi	dys-eutrophic	60 45′	27 00′	2.6
4	Suolijärvi	dys-oligotrophic	60 40′	24 40′	180
5	Tallisenlampi	oligotrophic	61 00′	28 00′	3.4
6	Vihmasaarenj.	dys-oligotrophic	69 00′	27 40′	15
7*	Inarinjärvi	oligotrophic	69 00′	27 40′	10^5
8	Melkutin	oligotrophic	61 45′	24 10′	70
9	Kilpisjärvi	oligotrophic	69 00′	21 40′	3300
10	Mutkajärvi	dys-oligotrophic	69 10′	28 20′	5
11	Valkeinen	oligotrophic	62 10′	24 50′	9.4
12	Toramolampi	dys-oligotrophic	66 30′	25 40′	20
	River				
13	Lemmenjoki	oligotrophic	68 50′	26 20′	
14	Nukkumajoki	oligotrophic	68 50′	27 10′	
15	Tsurnajoki	oligotrophic	69 20′	28 40′	

* Inarinjärvilake, 7_1 Ukonselkä, 7_2 Kasariselkä, 7_3 Vasikkaselkä, 7_4 Tsurnuvuono.

limnological lake type is very abstract and the dividing lines between different types are loose. Clearcut types are seldom found. Therefore the identification is based on numerous chemical, physical and biological analyses. The following water analyses belong in a basic limnological investigation: temperature, oxygen content, electrolytic conductivity, $KMnO_4$ consumption, water colour, depth of visibility and pH. In addition to these we determined also the concentrations of Na-, K- and Ca-ions, the total β-activity and the ^{137}Cs content of the water. Table 2 lists the results of the limnological and radiochemical analyses of the fresh waters studied.

A part of the water analyses were carried out by the Bureau for Fishery Investigations. The water samples were collected from each water layer with a Ruttner water-catcher.

As can be seen, the electrolytic conductivity diminishes from eutrophy towards oligotrophy. The potassium permanganate consumption depends on the amount of humus and other oxidizing organic matters. The values in dystrophic lakes are more than 35 mg/l. In oligotrophic lakes the $KMnO_4$ consumption is small. The colour of the water was determined colorimetrically, the values in dystrophic and eutrophic waters were the highest. In the former type this is caused by humus and in the latter by clay or plankton sediments. In the oligotrophic lakes the colour values are small. The colour of the water is greenish or blue-green. The depth of visibility was measured with a white disk, the so-called Secchi disk. The visibility is greatest in oligotrophic lakes. The eutrophic lakes are slightly basic and dys-oligotrophic lakes acid. Alkali metal concentrations diminish from eutrophy to oligotrophy. The total β-values and ^{137}Cs values of the water do not seem to correlate with the lake type.

There is an exceptional lake in Tables 1 and 2, lake no. 8. Its conductivity and alkali-metal concentrations are higher than its place on the trophic scale would indicate. The lake has been placed as no. 8 on the basis of the results of other water analyses and other biological considerations.[(3)]

Fish samples were collected altogether from twelve lakes and three rivers and represent fourteen different fish species. The weight of the samples varied 0.5–2 kg. In each sample the lengths and weights of the biggest, of a medium-sized one, and of the smallest fish were determined.* Scales or the operculum bone

* The mean length and age of the fish reported in the tables were calculated from these three individuals, but the mean weight from the total weight of the sample.

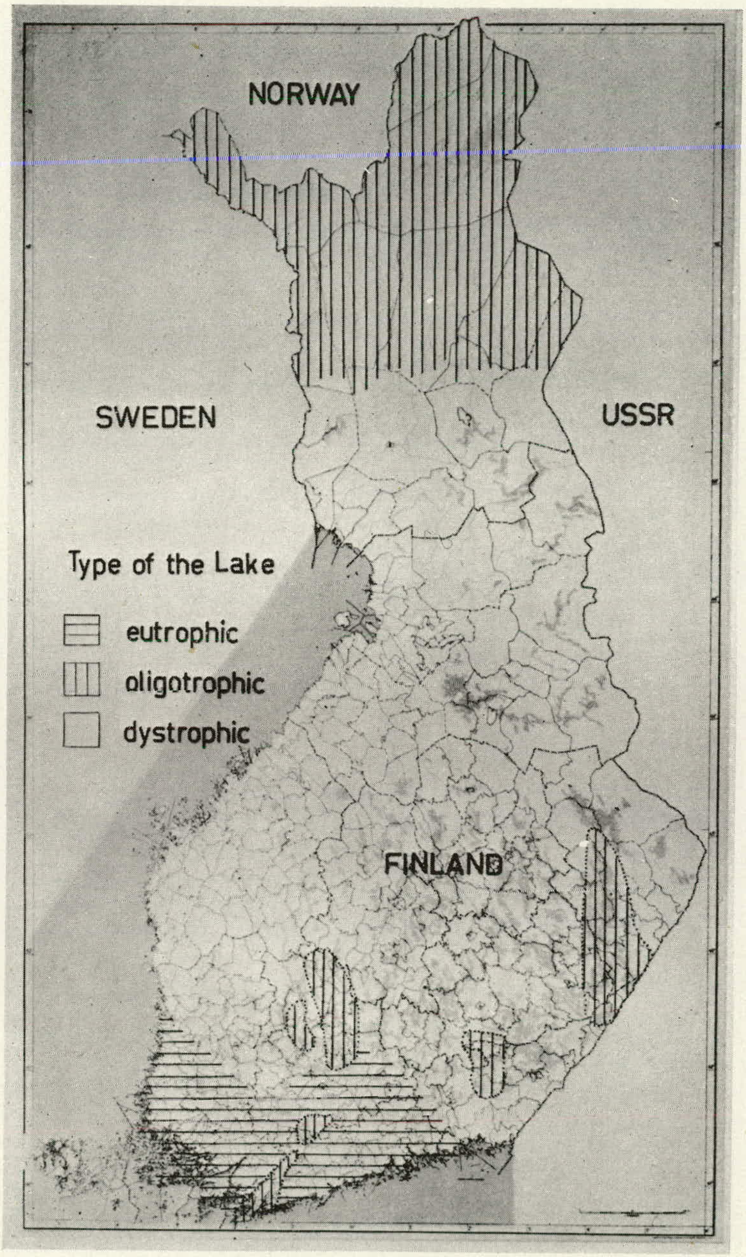

FIG. 1. The main regions of different lake types in Finland.

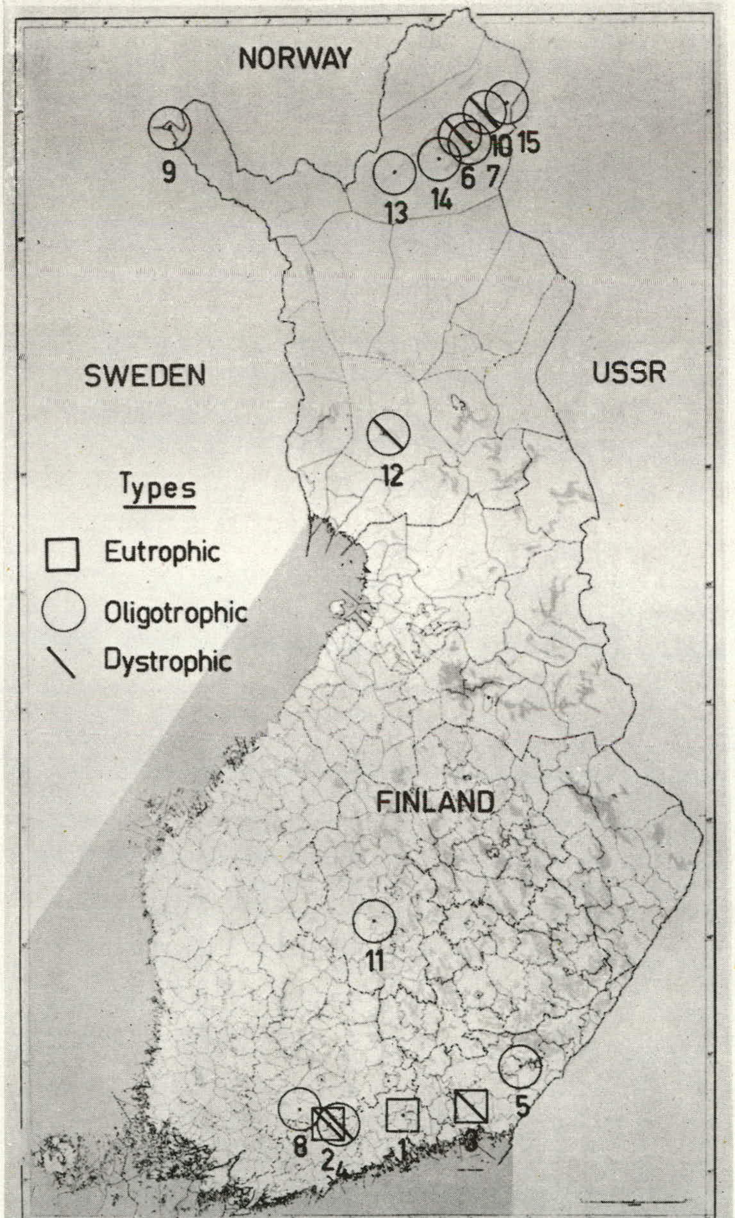

FIG. 2. Lakes and rivers of this investigation. For data see Table 1.

Table 2: Limnological analyses of fresh waters under study (cf. Table 1)

Lake	Date	Conductivity (mho, 18°C)	$KMnO_4$-consumption (mg/l.)	Colour Pt, (mg/l.)	Visibility (m) Secchi reading	pH at 0 m	Na* (mg/l.)	K* (mg/l.)	Ca* (mg/l.)	^{137}Cs (pc/l.)	Tot.-β (pc/l.)
1	16/7/64	79	70	100	0.5	7.9	4.3	2.0	4.0	0.82	26.0
2	14/7/64	72	50	85	0.5	8.0	3.5	2.0	5.7	0.28	40.5
3	2/8/63	40	34	35		7.3	1.9		6.3		18.6
4	14/7/64	43	39	50	2.2	7.3	2.3	1.0	3.1	0.79	35.8
5	7/8/63	31	15	15		7.4	2.2		2.8		10.8
6	21/7/64	23	40	80		6.1	1.4	0.7	1.5		22.3
7_1	20/7/64	27	24	20	4.3	7.1	1.5	0.4	1.6		19.4
7_3	22/7/64	23	22	10	9.0	7.0	1.5	0.5	1.4	1.50	15.8
7_4	23/7/63	17									14.6
8	25/5/64	46	12	5	9.7	7.4	2.0	1.0	2.9	0.45	12.9
9	16/8/63	24	12	5	9.5		1.2				11.0
10	23/7/64	16	144	100		5.3	1.3	0.2	1.0		35.3
11	27/8/63	13	8	5		6.4	0.7		1.3		17.9
12	7/9/63	11	53	35		6.1	0.9		1.0		39.7
13	25/7/63	26					1.7				9.9
15	22/7/63	17					1.3				

* Determined by flame photometry. Ca values by this method are systematically about one-third lower than, for example, by atomic absorption spectrophotometry.

were collected for age determination and samples of the stomach content were taken to determine the nature of the food intake. On the basis of these analyses and general knowledge on the feeding habits of fish a picture has been formed of the food intake of the sample fish.

The entrails were removed from the fish and they were transported fresh to the Institute enclosed in plastic bags in coolers filled with solid CO_2.

The fish were dried at 100–110°C for 3–4 days, ground and packed in a 0.5-l. plastic container and analyzed γ-spectrometrically with a 512-channel pulse height analyzer in which a 3×5 in. crystal was used as the detector. Each sample was measured for 1 hr and in the ^{137}Cs determinations the value of 2σ varied as follows: when the ^{137}Cs content was 0.1 nc/kg (fresh weight), 2σ was ± 14 per cent and when the ^{137}Cs content was 5.0 nc/kg (fresh weight) 2σ was $\pm 1\%$. In the potassium determination 2σ was about ± 6 per cent.

Table 3 contains the results on the three fish species having the highest ^{137}Cs contents. The perch, when young, eats bottom fauna but when over 20 cm it becomes piscivorous; the pike is one of the most typical predators. The burbot eats both bottom fauna and small fish. In all the above fish the ^{137}Cs content increases from eutrophic to oligotrophic lakes. There is a relationship between the electrolyte content of the water and the ^{137}Cs content of the fish in such a way, that the lower the electrolyte content (and the electrolytic conductivity) the higher the ^{137}Cs content of the fish.

The activity of perch seemingly does not obey this relationship well. This is, however, due to the fact that the perch sampled had partially fed on bottom animals, partially on small fish. For example, the perch of lake no. 4 had fed solely on small fish, which evidently explains their relatively high ^{137}Cs content. All species in lake no. 8 contain more ^{137}Cs than could be supposed on the basis of the electrolytic conductivity alone. As mentioned before, this lake is exceptional, being highly oligotrophic in spite of moderate conductivity.

All the fish in Table 4 are so called non-fish-eating species. The roach and bream eat bottom fauna. The white-fish consumes bottom fauna or plankton or both. The ^{137}Cs content of the roach and bream increases again steadily from

Table 3. Analyses of predatory fish from the lakes under study

Lake no.	Date 1963	Sample no.	Mean, total fish weight (g)	length (cm)	age (yr)	Dry weight, per cent of fresh weight, entrails removed	^{137}Cs nc/kg fresh weight	g K/kg fresh weight
Perch (*Perca fluviatilis* L.)								
1	12/6	47	40	17	4	26.4	0.19	3.1
3	2/8	169	70	19	6	29.2	1.55	3.4
4	28/6	70	80	20	9	26.8	3.69	4.0
5	7/8	227	25	14	5	24.4	2.66	3.3
6	20/7	97	85	20	6	28.7	2.43	2.9
7_1	17/7	86	110	20	5	25.4	3.13	3.5
8	13/7	79	120	21	8	25.4	6.76	3.5
11	27/8	221	25	15	3	25.4	16.1	4.5
12	7/9	201	50	17	5	25.1	20.4	3.5
Pike (*Esox lucius* L.)								
1	12/6	49	270	36	4	22.9	0.16	3.6
3	2/8	170	160	30	7	23.0	1.45	3.3
5	7/8	175	360	39	4	23.3	2.80	3.6
7_2	20/7	90	670	50	6	23.8	4.07	3.2
8	2/9	225	150	28	4	20.7	4.88	3.3
10	21/7	101	1150	60	8	25.6	11.7	3.9
11	27/8	223	80	25	3	22.0	15.8	4.0
12	7/9	202	130	30	4	21.3	16.2	3.3
Burbot (*Lota vulgaris* L.)								
4	28/6	71	350	35		16.9	1.53	2.0
7_2	20/7	94	530	35		18.9	3.28	2.3
12	7/9	199	190	30		20.0	7.67	2.6

eutrophic to oligotrophic. The activity level of the white-fish does not fluctuate much in different lakes, since white fish is usually found only in oligotrophic lakes. The differences found (max. twofold) are probably caused for the most part by the differences in food intake. The forms feeding on bottom fauna have been found to have the highest activity levels.

Table 5 illustrates the results on the other fish species, of which only a few samples have been obtained from different lakes. Their activity level conforms to the lake type, but the level is greatly affected also by the foods consumed by the fish species. The European cisco feeds on plankton; perch-pike, trout, and char are predators, the others feed on bottom fauna.

Differences in the ^{137}Cs levels between fish species probably are caused by differences in food consumption. In the fish species consuming bottom fauna the ^{137}Cs content is 1.2–3 times, and in the predatory fish 3–5 times that of the plankton-consuming fish.

The ^{137}Cs level of fish has increased from the year 1962 to the year 1963 about 1.5 times and on the basis of the results of the measurements done in summer 1964 the level seems again to have about doubled.

It is interesting to compare our results with those reported from Italy for the summer of 1963.[4] One of the species analyzed in the Italian study was perch, which also was analyzed in our study. Our ^{137}Cs values vary from 0.2 to 20.4 nc/kg. In the four Italian lakes studied, the Lake Maggiore, Varese, Comabbio and Monate, the values were, in June 1.1, 1.2, 2.8 and 7.4 and in September 1.9, 3.3, 5.2 and 6.3 nc/kg, respectively. These values are about in the middle of our range. As can be seen the values

Table 4. Analyses of non-predatory fish from the lakes under study

Lake no.	Date 1963	Sample no.	Mean, total fish weight (g)	length (cm)	age (yr)	Dry weight per cent of fresh weight, entrails removed	^{137}Cs nc/kg fresh weight	g K/kg fresh weight
Roach (*Leuciscus rutilus* L.)								
1	12/6	56	40	16	5	25.0	0.10	2.6
2	28/6	65	70	20	7	22.0	0.28	2.6
3	2/8	171	110	22	10	26.8	1.17	3.3
5	7/8	176	40	17	7	26.7	1.94	3.7
8	13/7	76	55	19	6	23.4	2.19	3.4
11	27/8	222	550	36	10	27.0	4.73	3.5
12	7/9	200	220	26	8	25.2	7.54	3.4
Bream (*Abramis brama* L.)								
1	12/6	48	130	23	3	25.9	0.10	3.4
2	28/6	68	210	26	6	25.4	0.25	3.2
3	2/8	213	60	20	4	23.6	0.71	3.6
5	7/8	172	200	27	9	24.6	1.48	3.3
Whitefish (*Coregonus*)								
7_1*¶	17/7	85	220	29	6	22.8	1.34	3.4
7_2*¶	20/7	95	300	32	5	24.1	1.57	3.6
7_2†	19/7	96	450	36	9	23.1	1.18	2.4
7_4†	21/7	103	410	35	6	24.0	1.52	3.1
7_2‡	19/7	88	40	18	4	23.5	1.55	2.9
7_3§¶	7/8	177	755	40	7	25.8	1.48	2.5
7_4§	22/7	105	420	35	4	25.9	1.43	2.9
8‖	13/7	78	360	33	5	24.2	0.86	3.6
9‖¶	16/8	197	200	28	5	26.2	1.82	3.3
13‖¶	25/7	117	200	28	4	24.8	1.34	3.4

* *Coregonus holsatus Thien f. Inarensis* Järvi
† *C. wartmanni Bl. f. borealis Järvi*
‡ *C. wartmanni* Bl.
§ *C. fera. Jur. f. inarensis* Järvi
‖ *C. lavaretus* L. coll.
¶ bottom feeders.

were approximately doubled from June to September 1963 in the three first lakes studied. It is evident that our lakes represent a much wider range of limnological conditions.

SUMMARY

The results can be summarized in the following way. It has been established that the ^{137}Cs level in fish depends on
(a) the limnological type of the lake,
(b) the nature of the foods consumed by the fish.

A negative correlation exists between the electrolytic conductivity and the ^{137}Cs activity level of the fish. In all probability ^{137}Cs is resorbed in waters low in electrolytes more efficiently by the phytoplankton and further enriched through food chains, than in waters rich in electrolytes. In further studies we will attempt to clarify the intake of ^{137}Cs through the gills in connection with the osmoregulation process. We also hope to obtain more precise

Table 5. Analyses of miscellaneous fish species from the lakes under study

Lake no.	Date 1963	Sample no.	Mean, total fish weight (g)	Mean, total fish length (cm)	Age (yr)	Dry weight per cent of fresh weight, entrails removed	^{137}Cs nc/kg fresh weight	g K/kg fresh weight
White bream (*Abramis blicca* Bloch)								
1	12/6	50	50	20	10	23.8	0.08	2.7
2	28/6	67	280	25	11	24.8	0.13	2.9
Perch-pike (*Lucioperca sandra* L.)								
2	28/6	66	1750	59	10	24.7	0.78	3.9
European cisco (*Coregonus albula* L.)								
4	28/7	69	100	25	4	26.5	1.44	4.2
Trout (*Salmo trutta lacustris* L.)								
7_1	17/7	87	320	33	5	25.3	3.88	3.8
7_2	21/7	102	300	30	5	22.2	2.51	2.8
7_3	7/8	226	1200	49	8	34.9	6.53	3.9
Brown trout (*Salmo trutta fario* L.)								
14	25/7	118	100	20	4	21.8	3.52	2.4
15	22/7	104	70	20	3	24.1	6.09	3.6
Char (*Salmo salvelinus salvelinus* L.)								
7_2	21/7	99	340	33	5	23.4	2.42	2.9
9	16/8	198	480	35	5	27.2	2.32	2.8
Arctic char (*Salmo salvelinus alpinus* L.)								
7_4	23/7	106	300	30	5	20.2	1.90	2.1
Grayling (*Thymallus vulgaris* L.)								
7_2	18/7	89	350	35	5	27.1	1.32	3.4
7_2	25/7	107	750	43	6	24.3	1.88	3.5

information on the biological half-time of the ^{137}Cs in fish and on the activity levels of the different links of the food chain in different types of lakes.

Acknowledgement—Financial support for this investigation by the Finnish Atomic Energy Commission and the U.S. Department of Health, Education and Welfare (Public Health Service Research Grant No. RH-307-01) is gratefully acknowledged.

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Reprinted from
RADIOECOLOGICAL CONCENTRATION PROCESSES
Proceedings of an International Symposium held in Stockholm 25–29 April, 1966
PERGAMON PRESS — OXFORD & NEW YORK — 1966

^{137}Cs IN FINNISH LAPPS AND OTHER FINNS IN 1962–6

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INVESTIGATIONS of the food-chain lichen–reindeer–man were started by our group in 1960 by analyses of lichen and reindeer meat[1] and by a dietary survey of the Lapps.[2] The first whole body-counting was carried out in October 1961 in collaboration with Dr. Lidén's Swedish group.[3] Since then some 100 Lapps have been counted each year. Since a detailed report of the first survey[3] and later reports on body-burdens[4, 5] and ^{137}Cs in the diet[6] of the Lapps have been published, only a brief summary of the whole body data from the years 1962–6 is presented in this paper with some data on reindeer meat and a discussion of the biological half-time of ^{137}Cs in the lichen.

HUMAN BODY-BURDENS OF ^{137}Cs

Body-burdens of ^{137}Cs in Lapps from 1962 to 1966 are presented separately for both sexes in Tables I to VI and as mean of males and females in Fig. 1. The values obtained in April approach

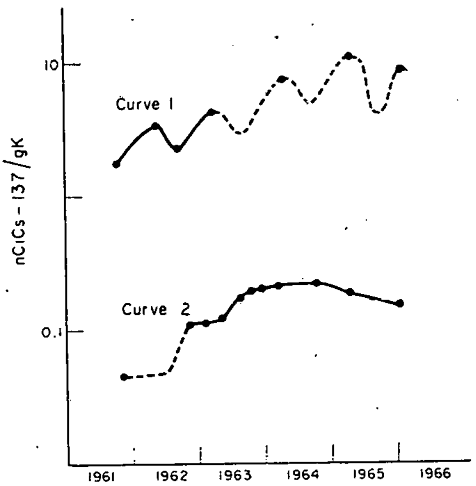

FIG. 1. ^{137}Cs body-burdens (nCi/g K) of adult Finnish Lapps—reindeer breeders—and of the southern Finns, 1961–6. Mean for men and women. *Curve 1:* Lapps. *Curve 2:* Southern Finns.

the annual maximum, because in Inari the reindeer meat consumption is greatly diminished from April onwards:[6] consumption in May is already less than half of the winter rate. Because the winter rate of consumption is again reached in October, the body-burdens are closer than 80% of the saturation already in March. Values for adults of about 20 years of age from the southern Finland are included in the tables for comparison.

Table I. Body-burden of ^{137}Cs in adult (20–50 years) Finnish Lapps in May 1962

	Subjects	Age (years)	^{137}Cs			K	
			nCi	nCi/kg	nCi/g K	g	g/kg
ENONTEKIÖ							
Men: Reindeer breeders	27	36 (23–49)	449	6·91	4·12	109	1·61
Women: Reindeer breeders	19	38 (22–47)	242	4·17	2·88	84	1·32
INARI							
Men:							
Reindeer breeders	20	35 (23–49)	499	7·84	3·56	140	2·12
Reindeer breeding fishers	16	35 (23–50)	322	5·18	2·21	146	2·29
Lapps of other occupations	11	34 (20–48)	187	3·05	1·40	134	2·19
Women:							
Reindeer breeders	10	31 (22–50)	238	4·01	2·80	85	1·44
Reindeer breeding fishers	6	40 (34–47)	137	2·38	1·47	93	1·62
Lapps of other occupations	6	38 (24–50)	71	1·31	0·75	95	1·77
UTSJOKI							
Men:							
Reindeer breeders	12	34 (23–47)	299	4·73	2·17	138	2·15
Reindeer breeding fishers	3	41 (37–47)	391	5·86	2·51	156	2·34
Lapps of other occupations	13	32 (23–44)	151	2·49	1·19	127	2·10
Women:							
Lapps of other occupations	13	37 (26–49)	129	2·34	1·55	83	1·47
SKOLTS							
Men: Lapps of other occupations	10	32 (22–43)	148	2·40	0·93	160	2·60
Women: Lapps of other occupations	6	32 (30–37)	95	1·69	0·96	99	1·69

Table II. Body-burden of ^{137}Cs in adult (20–50 years) Finnish Lapps in September 1962

	Subjects	Age (years)	^{137}Cs nCi	^{137}Cs nCi/kg	^{137}Cs nCi/g K	K g	K g/kg
INARI							
Men:							
Reindeer breeders	9	32 (25–49)	307	5·05	2·15	143	2·35
Reindeer breeding fishers	5	35 (23–46)	180	2·80	1·27	142	2·19
Lapps of other occupations	5	41 (31–48)	132	2·27	0·98	135	2·28
Women:							
Reindeer breeders	2	25 (23, 26)	206	3·37	2·45	84	1·44
Reindeer breeding fishers	1	41	84	1·67	1·20	70	1·40
Lapps of other occupations	2	39 (37, 40)	85	1·50	0·96	89	1·70
UTSJOKI							
Men:							
Reindeer breeders	6	34 (23–47)	204	3·22	1·52	134	2·04
Lapps of other occupations	2	25 (23, 26)	120	2·24	0·82	146	2·76
Women:							
Lapps of other occupations	1	45	63	0·79	0·93	68	0·85
SKOLTS							
Men: Lapps of other occupations	1	34	36	0·61	0·29	124	2·12
Women: Lapps of other occupations	1	32	25	0·35	0·24	104	1·46

Table III. Body-burden of ^{137}Cs in adult (20–50 years) Finnish Lapps in March 1963

	Subjects	Age (years)	^{137}Cs			K	
			nCi	nCi/kg	nCi/g K	g	g/kg
Enontekiö							
Men: Reindeer breeders	14	37 (24–50)	592	8·76	3·94	150	2·24
Women: Reindeer breeders	11	38 (26–47)	246	4·24	2·68	92	1·54
Inari							
Men:							
Reindeer breeders	10	34 (25–48)	645	10·17	4·42	146	2·30
Reindeer breeding fishers	2	41 (38, 44)	403	5·80	2·86	141	2·00
Lapps of other occupations	3	42 (32–49)	204	3·41	1·51	135	2·25
Women:							
Reindeer breeders	4	32 (23–41)	425	6·46	3·79	112	1·73
Reindeer breeding fishers	2	42 (39, 44)	143	2·42	1·44	99	1·65
Lapps of other occupations	2	44 (41, 47)	128	2·46	1·44	89	1·71
Utsjoki							
Men:							
Reindeer breeders	2	44 (39, 48)	420	4·88	2·52	167	2·07
Reindeer breeding fishers	2	43 (38, 48)	303	4·37	2·75	110	1·59
Lapps of other occupations	4	26 (24–27)	202	3·54	1·52	133	2·28
Women:							
Lapps of other occupations	7	39 (27–50)	160	2·86	1·67	96	1·59
Skolts							
Men: Lapps of other occupations	1	23	127	2·03	0·87	146	2·34
Women: Lapps of other occupations	2	36 (33, 38)	142	2·40	1·43	99	1·55

Table IV. Body-burden of ^{137}Cs in adult (20–50 years) Finnish Lapps in April 1964

	Subjects	Age (years)	^{137}Cs nCi	^{137}Cs nCi/kg	^{137}Cs nCi/g K	K g	K g/kg
INARI							
Men:							
Reindeer breeders	15	38 (25–51)	1262	19·51	8·36	151	2·36
Reindeer breeding fishers	11	38 (25–52)	863	13·56	6·08	142	2·21
Lapps of other occupations	6	37 (22–50)	591	12·09	4·34	136	2·20
Women:							
Reindeer breeders	6	33 (24–52)	580	8·59	4·83	120	1·65
Reindeer breeding fishers	4	31 (36–45)	414	6·92	4·14	100	1·64
Lapps of other occupations	2	50 (48, 52)	329	6·04	3·62	91	1·67
UTSJOKI							
Men:							
Reindeer breeders	9	36 (25–49)	753	11·72	5·50	137	2·10
Reindeer breeding fishers	3	43 (39–49)	659	9·57	4·46	148	2·16
Lapps of other occupations	8	33 (25–46)	309	4·92	2·26	137	2·17
Women:							
Lapps of other occupations	11	40 (28–51)	243	4·16	2·93	83	1·45
SKOLTS							
Men: Lapps of other occupations	4	34 (24–45)	386	5·84	2·70	143	2·43
Women: Lapps of other occupations	5	34 (32–39)	293	5·16	2·79	105	1·97

Table V. Body-burden of ^{137}Cs in adult (20–50 years) Finnish Lapps in April 1965

	Subjects	Age (years)	^{137}Cs nCi	^{137}Cs nCi/kg	^{137}Cs nCi/g K	K g	K g/kg
INARI							
Men:							
Reindeer breeders	7	39 (26–52)	1437	23·25	10·64	134	2·16
Reindeer breeding fishers	9	37 (26–47)	744	11·28	5·49	133	2·05
Lapps of other occupations	5	44 (34–51)	513	8·87	4·19	124	2·04
Women:							
Reindeer breeders	3	41 (26–53)	1018	14·64	10·43	96	1·38
Reindeer breeding fishers	3	41 (37–46)	429	7·32	4·81	89	1·52
Lapps of other occupations	2	38 (33, 43)	244	4·22	3·34	75	1·30
UTSJOKI							
Men:							
Reindeer breeders	4	43 (37–50)	757	9·80	4·64	153	2·13
Reindeer breeding fishers	3	44 (40–50)	670	9·52	5·01	135	1·90
Lapps of other occupations	7	36 (27–47)	486	7·70	4·03	117	1·93
Women:							
Lapps of other occupations	10	41 (29–52)	326	5·96	4·22	79	1·47
SKOLTS							
Men: Lapps of other occupations	4	38 (25–46)	273	4·79	2·37	114	2·04
Women: Lapps of other occupations	5	35 (33–40)	231	4·14	3·00	75	1·35

Table VI. ^{137}Cs body contents of Finnish Lapps in 2 April 1965 and 26 March 1966 compared. The same individuals measured in both years

	Subjects	Age (years)	^{137}Cs body burden (nCi per person)		Average in March 1966 (% of average in April 1965)
			April 1965	March 1966	
Males					
INARI					
Reindeer breeders	5	41	1557	1245	79·9
Reindeer breeding fishers	5	39	876	715	81·6
Lapps of other occupations	4	47	475	547	115·2
Average	14	42	1005	856	85·2
UTSJOKI					
Reindeer breeders	4	44	758	519	68·5
Reindeer breeding fishers	3	45	670	676	100·9
Lapps of other occupations	4	39	534	462	86·5
Average	11	42	652	541	83·0
All males, average	25	42	850	717	84·4
Females					
INARI					
Reindeer breeders	2	49	977	794	81·3
Reindeer breeding fishers	2	40	423	345	81·6
Lapps of other occupations	2	39	244	307	125·8
Average	6	43	548	482	88·0
UTSJOKI					
Lapps of other occupations	8	42	382	315	82·4
All females, average	14	42	453	386	85·2
All Lapps, average	39	42	707	599	84·7

As can be seen, a continuous increase is visible in the spring values since 1962. The annual increase was—in different Lapp groups—30–80% from May 1962 to March 1963, about 100–200% the next year, and about 15% from April 1964 to April 1965.† Caesium-137 body burdens of the Inari reindeer breeders are comparable with the highest values simultaneously registered in Alaska[7] and Sweden.[8] In Alaska the body burdens of Eskimos reach the maximum values in summer.[7] In Sweden, too, maxima are reached later in the spring, and the summer minimum is less deep than in Inari—evidently due to different seasonal change of the diet (e.g. better accessibility of refrigerators in Sweden).[3] Mean values obtained in Finland, Sweden and Alaska from 1962 to 1964 are compared in Table VII, and it is striking how close to each other the values are. From the U.S.S.R.[9] somewhat higher individual maximum values are reported than from Finland. The individual values are compared in Table VIII. The maximum values reported from the U.S.S.R. for July 1962 and 1963 are astonishingly high—two or three times higher than the spring maximum in Finland in the same year. It is possible that reindeer meat consumption is greater in summer in the U.S.S.R. So far, no dietary data have been published from there, however. In the spring 1964 the Russian maximum value is only 38% higher than the simultaneous Finnish one, which could mean that the levels in reindeer are nearly equal because we did not get to the measurement in 1964 several of the most radioactive men from the earlier measurements. The broad similarity of values is understandable because ^{137}Cs is mainly of stratospheric origin and the global fallout is very similar along the same

† From April 1965 to March 1966, however, the body-burdens decreased by about 15% (Table VI).

latitude throughout the world. The ^{137}Cs content of lichens and the body-burdens of reindeer and caribou therefore are similar, and persons who eat the highest amount of meat of these animals also have similar body-burdens.

Table VII. ^{137}*Cs body-burdens in reindeer breeders and Eskimos, 1962–5*

Finland Inari male Lapps			Sweden Jokkmokk male Lapps[8]		Alaska Anaktuvuk Pass Eskimos[7]	
Date	nCi	nCi/kg	Date	nCi/kg	Date	nCi
5/62	500	7·8	4/62	8·15	7/62	480
3/63	645	10·2	4/63	9·45	6/63	630
4/64	1260	19·5	2/64	15·0	7/64	1250
4/65	1440	23·3	2/65	17·5		

Table VIII. ^{137}*Cs body-burdens of reindeer breeders in Finland and U.S.S.R., 1962–5*

	Finland				U.S.S.R.	
	Aver.	Min.	Max.		Min.	Max.
Date	(nCi/gK)			Date	(nCi/gK)	
5/62	3·56	1·0	6·4	7/62	1·5	12·9
3/63	4·42	1·9	7·8	7/63	3·6	23·6
4/64	8·36	5·0	18·6	3/64	7·3	25·7
4/65	10·64	8·7	19·6			

^{137}Cs IN CUMULATIVE FALLOUT, LICHEN AND REINDEER

Finnish results on ^{137}Cs in the cumulative fallout,[10] lichen and reindeer meat are presented in Fig. 2 and Table IX. As can be seen, the ^{137}Cs deposition in 1963 (19·4 nCi/km^2) was about two times greater than in 1962 or 1964. As more than half of the deposition in 1963 was deposited in the latter part of the year it is not yet visible in the lichen sample collected in July 1963. Therefore the increase in lichen from July 1963 to July 1964 becomes high. Our lichen value for July 1964 may be a little too high, too, in view of the precipitation data. Three samples evidently is not a sufficient number, although they would be relatively large and carefully taken. That there has been evidently, although not necessarily as the deviations overlap, true decrease in the ^{137}Cs content of the lichen, is corroborated by the reindeer meat activities: there was 8% decrease in the mean value from December 1964 to December 1965.

^{137}Cs IN DIFFERENT MUSCLES OF REINDEER

In order to determine with sufficient statistical accuracy the biological diversity and other variability of the ^{137}Cs content of reindeer meat, as well as the difference between the sexes, three different meat samples—joint, shoulder and sirloin—were taken in March 1964 from 10 male and 10 female animals of about 3 years of age. Each sample was individually analysed for ^{137}Cs and ^{40}K by gamma spectrometry. The results are presented in Table X.

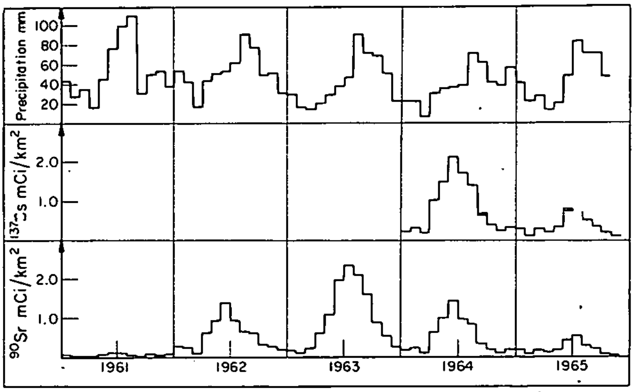

FIG. 2. Deposition of ^{137}Cs and ^{90}Sr in Finland/Salo.[14]

Table IX. Deposition of ^{137}Cs in Finland (Salo[10]) and ^{137}Cs contents of lichen and reindeer meat, 1961–5

	Deposition ^{137}Cs mCi/km²		Lichen						Reindeer meat			
	Annual	Cumul.[a]	Date	nCi/kg dry wt. Min.–max.	Mean ±σ	No. of samples	Annual increase or decrease nCi/kg	mCi/km²	Date	nCi/kg fresh wt.	±σ	No. of samples
1960		24·0 [b c]										
1961	1·3 [c]	24·7	8/61	8–34	16 ±3·5	(5) [d]			10/61	15·8		(2)
1962	10·6 [c]	34·7	7/62	15–28	22 ±3	(15) [e]	+6	+4	2/62	17·2		(2)
1963	19·4 [c]	53·3	7/63	37–38	37 ±0·5	(3)	+15	+9	3/63	48·0		(12)
									3/64	50·0	±4	(60)
1964	10·2	63·3	7/64	54–69	64 ±8	(3)	+27	+16	12/64	60·1	±5	(6)
									4/65	72·3	±9	(4)
1965	4·3	66·1	8/65	53–59	56 ±3	(3)	−8	−5	12/65	55·3	±9	(4)

[a] Corrected for decay to the end of each year.
[b] For the 1960 value (end of year) that of ^{90}Sr for Leningrad (15 mCi/km²) (Ref. 9) is used.
[c] Calculated from ^{90}Sr data using $^{137}Cs/^{90}Sr$ ratio 1·6.
[d] Ref. 15.
[e] Ref. 16.

As can be seen, there is a great standard deviation, 47%, for the individual value of joint in males. In females the deviation is only 12%. The ^{137}Cs-content of females is 22% lower than that of males, that of sirloin 7% lower than that of joint or shoulder. A very large number of samples from males is needed for a representative combined sample. One standard deviation for a group of 10 samples was still over 8%. For 10 female samples it was only 1·7–2·2%. Evidently the physiological variability among the males, some of which are, for example, castrated, is much greater than among the females, although the age limits for the males were somewhat wider in the above material.

DISCUSSION

An interesting question is the future change in the ^{137}Cs body-burdens of reindeer and Lapps if the test ban continues and the Lapps do not change their diet.

Table X. ^{137}Cs *and* K *in tissues of reindeer, slaughtered at Karigasniemi, Finnish Lapland, 18–19 March 1964*
Samples from 10 male, 10 female animals: age of the males 1–6 years, mean 2·9 years; age of the females 2–5 years, mean 3·3 years. Average of all samples 49 ± 4 (σ) nCi ^{137}Cs/kg fresh meat. Statistical accuracy of counting $\pm 0{\cdot}5$ to 1% for ^{137}Cs; about ± 15% for ^{40}K

	Joint			Shoulder			Sirloin		
	^{137}Cs nCi/kg	K g/kg	Dry wt. %	^{137}Cs nCi/kg	K g/kg	Dry wt. %	^{137}Cs nCi/kg	K g/kg	Dry wt. %
Males									
Min.	36·2	3·4	24·5	36·5	3·0	24·5	33·6	1·9	23·0
Max.	115·3	4·5	29·0	122·8	5·1	29·0	112·8	5·1	34·8
σ	26·2	0·35	1·56	28·2	0·52	1·78	26·6	0·96	3·42
Mean	56·3	4·0	26·6	55·7	3·8	26·5	52·1	3·7	28·8
$\sigma/\sqrt{M10}$	8·3	0·11	0·49	8·9	0·16	0·56	8·4	0·30	1·08
Females									
Min.	33·0	3·0	25·0	32·3	3·2	25·0	31·9	2·4	26·5
Max.	52·6	5·2	28·0	50·9	4·9	26·5	56·3	5·5	33·3
σ	5·28	0·67	0·97	5·73	0·61	0·67	6·82	1·05	2·09
Mean	44·2	3·8	26·4	40·7	4·0	25·7	43·3	4·4	29·0
$\sigma/\sqrt{M10}$	1·67	0·21	0·31	1·81	0·19	0·21	2·16	0·33	0·66

The body-burdens of Lapps as well as those of reindeer will depend directly on the ^{137}Cs content of the lichen, which again will be determined by:

(1) additional deposition of ^{137}Cs;
(2) washout of ^{137}Cs from the lichen;
(3) consumption of lichen by the reindeer;
(4) physical decay of ^{137}Cs.

As was seen from Table IX, the ^{137}Cs deposition increased in 1965 by 4·4%, but our values for lichen and reindeer meat decreased by 12% and 8%, respectively. According to these figures lichen would have lost some 12–16% of its ^{137}Cs due to washout, physiological decay and consumption by the reindeer. This would correspond to a "biological half-time" of about 4–5 years. Though short, this is not impossible, because the age of lichen in our lichen fields is estimated to be some 25 $\pm$ 5 years (T. Ahti, personal communication). The rotation time is much shorter, however, because the reindeer normally eats only the top part of the lichen. Alaruikka[11] gives 4–5 years for the renewal time after heavy grazing, Ahti[13] 5–10 years and Helle[17] 10 years. Ahti (*loc. cit.*) gives for the lichens an approximate growth rate of 3–5 mm/year depending, for example, on the species. The best pasture, 5–6 cm high, is thus 10–30 years old. A "half-time" of 10–13 years due to grazing would correspond to an annual loss of 5–6·6%. This would leave a 5–10% loss per year due to washout and physiological decay. These figures are still uncertain, but since the additional deposition will be this year only about 2 mCi/km², it will be easy to notice the decrease in the ^{137}Cs level this summer.

Acknowledgement.—This investigation has been supported by the Finnish Atomic Energy Commission and the U.S. Atomic Energy Commission (At(30-1)-3446).

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Reprinted from
RADIOECOLOGICAL CONCENTRATION PROCESSES
Proceedings of an International Symposium held in
Stockholm 25–29 April, 1966
PERGAMON PRESS — OXFORD & NEW YORK — 1966

^{137}Cs IN FISH, PLANKTON AND PLANTS IN FINNISH LAKES DURING 1964-5

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IT WAS observed in 1962 that the ^{137}Cs-content of fish in different types of lakes in Finland varied greatly.[1] This observation led to a series of investigations[2] which in 1964 were expanded to a systematic radioecological study. The object of this study has been the elucidation of the complete set of factors effecting the accumulation and transfer of radiocaesium from one trophic level to another in lakes of different limnological character.

Lakes are usually divided into two main types: *eutrophic* and *oligotrophic*. A eutrophic lake, i.e. one rich in nutrients, is characterized by the following features: its abundant production of phytoplankton, its varied stock of fish, and the high electrolyte content of the water. An oligotrophic lake, i.e. one low in nutrients, is characterized by a low production of phytoplankton, sparseness of littoral vegetation, clarity of the water, and low concentration of electrolytes. In addition, *dystrophy* is distinguished among lake types as a subgroup. A dystrophic lake is characterized by its more or less brown colour, caused by dissolved humic acids in the water. Dystrophy can exist alongside with both eutrophy and oligotrophy (dyseutrophy and dysoligotrophy) even though the latter is most prevalent.

Oligotrophic, clear watered lakes are usually situated in hill and gravel regions, e.g. in Lapland and in the Alps. Lakes in cultivated, fertile areas are eutrophic. The main distribution area of eutrophic lakes in Europe consists of Middle Europe, the Baltic countries, Denmark, southern Sweden, southern Finland and the Carelian isthmus. Most lakes in Fennoscandia and in other regions of the globe in the coniferous zone are dystrophic, a consequence of the swampy character of these regions. (Fig. 1).

Investigations of 26 lakes, four rivers, and of the Gulf of Finland have been carried out during 1963–5. All above-mentioned lake types are represented among them. Water samples were collected vertically for basic limnological analyses; results obtained for the lakes sampled in 1964 are presented in Table I giving their electrolytic conductivity, $KMnO_4$-consumption, and Na, K and Ca content. The lakes are ranked in the Table so that the lake type changes downward from eutrophy towards oligotrophy. The conductivity and K-content diminish from eutrophy towards oligotrophy. The biggest divergence in lakes in Table I was found in lake no. 3d, where the electrolyte content (e.g. Na and Ca) increased due to the presence of residual waste from a sulphite cellulose production plant.

The activity of fish is inversely proportional to the K-content of the water and also to its conductivity, as can be seen in Fig. 2. The point deviating from the others, as seen in Fig. 2, is the sample from lake 3d. Potassium acts in water as a non-isotopic carrier of ^{137}Cs, and since the inactive caesium content of water is extremely low (on the basis of preliminary results obtained by atomic absorption spectrophotometric determinations $<0{\cdot}005$ mg/l.), the K-content of water affects decisively the enrichment of ^{137}Cs. Correspondingly, the significance of the Ca-content of water as a carrier of ^{90}Sr[3] has been noted.

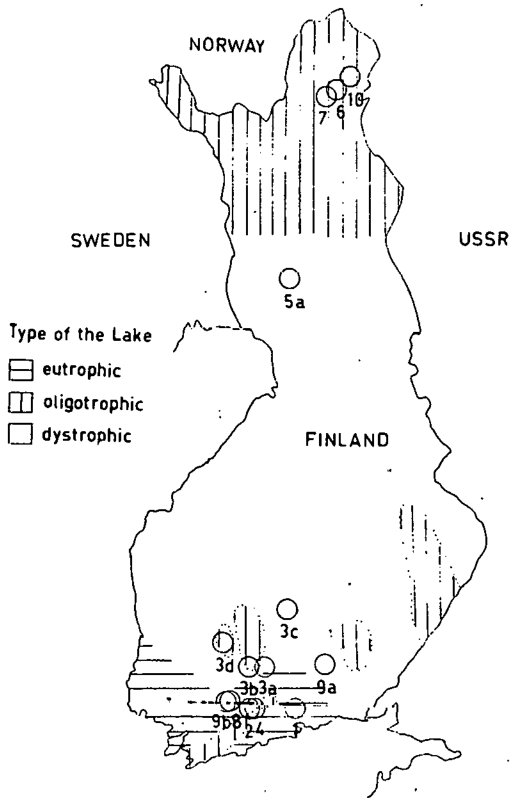

FIG. 1. Areas with different lake types in Finland and locations of lakes studied in this work (cf. Table I).

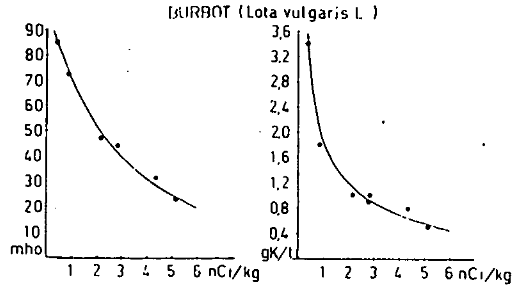

FIG. 2. ^{137}Cs-content of burbot in different types of lakes in summer 1964 as a function of conductivity (left graph) and potassium content (right graph) of the water.

Table 1. Limnological analyses of the lakes

No.	Lake	Date	Conductivity mho (18°C)	$KMnO_4$ cons. (mg/l.)	Na (mg/l.)	K (mg/l.)	Ca (mg/l.)	Limnological lake type
1	Niemenjärvi	9.9.65	85	75	5·2	3·5	8·8	Eutrophic
2	Kytäjärvi	8.9.65	72	45	3·0	1·8	7·4	Dyseutrophic
3a	Pyhäjärvi	19.9.65	71	32	3·5	2·4	8·0	Eutrophic
3b	Ilmoilanselkä	20.7.65	58	35	2·8	1·7	6·0	Eutrophic
3c	Päijänne	2.7.64	47	43	3·8	1·0	4·8	I:Eutrophic
3d	Näsijärvi	25.6.64	75	120	5·8	1·0	6·0	Dysoligotrophic
4	Suolijärvi	11.8.65	44	65	2·2	0·9	4·4	Dysoligotrophic
5a	Suonukkalampi	29.7.64	31	81	1·7	1·0	2·4	Dysoligotrophic
6	Vihmas.järvi	21.7.64	23	40	1·4	0·7	1·5	Dysoligotrophic
7_1	Inari	30.7.64	27	24	1·5	0·4	1·6	Oligotrophic
7_3	Inari	23.7.64	23	22	1·5	0·5	1·4	Oligotrophic
8	Melkutin	22.6.65	43	6	2·1	1·0	5·8	Oligotrophic
9a	Vuohijärvi	3.6.65	31	32	1·8	0·8	3·4	Oligotrophic
9b	Keritty	30.7.65	26		1·7	0·6	2·5	Dysoligotrophic
10	Mutkajärvi	23.7.64	16	100	1·3	0·2	1·0	Dysoligotrophic
10a	Akulampi	24·8·65	15		1·3	0·4	1·0	Dysoligotrophic

The electrolytic conductivity of water, which can be determined by a simple field analysis, gives a good indication of the ^{137}Cs-activity level of the biota in a virgin lake, because in an unpolluted lake the potassium-content is usually more or less directly proportional to the conductivity. In 1964 the ^{137}Cs-content of different lakes varied from 0·5 to 2·0 pCi/l.[2] The effect of the differences in the ^{137}Cs-content of water on the activity of fish was obscured by other factors.

The activity level of different fish species in a given lake varies so that piscivorous fish are 2 to 3 times more active than those eating bottom animals and plankton (Table II). Not only the activity level of food but also the biological half-time of ^{137}Cs in the species has an effect on the activity level. As a consequence, perch is the most active fish species (Table II), even though it feeds on plankton when young, on bottom animals during its growth period, and on small fish when full grown. The high activity level in perch is in all probability a consequence of the fact that its biological half-time of ^{137}Cs, *ca.* 200 days at 15°C, is considerably longer than that established for other fish species investigated (cf. Häsänen *et al.*[4]). The "trophic level" effect of Pendleton,[7] i.e. the fact that the excretion rate of potassium is 3 times greater than that of caesium, also effects the higher body burdens of predators.

A few fish samples from salt water were taken from the Gulf of Finland, about 30 km to the west from Helsinki. At the end of May 1964 the Baltic herring (*Clupea harengus*) contained 0·12 nCi ^{137}Cs/kg fresh weight, 11 July 1965 0·14 nCi/kg. In this later date flounder (*Pleuronectes flesus*) contained 0·23 nCi/kg and cod (*Gadus callarias*) 0·19 nCi/kg fresh wt. At the sampling place the salt concentration of water is about 4 to 5 *pro mille*. The ^{137}Cs content of the fish living in brackish water is only about one hundredth of that in the fish of nutrient deficient lakes. This is easily understandable because of the great difference between the electrolyte contents of the lake water and the brackish waters.

Table II. ^{137}Cs *content in some lakes during summer 1964*

				nCi per kg fresh weight				
No.	Lake	Conductivity (mho)	K (mg/l.)	Perch (*Perca fluviatilis*)	Pike (*Esox lucius*)	Burbot (*Lota vulgaris*)	Roach (*Leuciscus rutilus*)	Whitefish (*Coregonus* sp.)
1	Niemenjärvi	85	3·5	0·26	0·44	0·38	0·19	
2	Kytäjärvi	72	1·8	1·15	0·77	0·85	0·39	
3a	Pyhäjärvi	71	2·4	1·92	1·12		0·51	
3c	Päijänne	47	1·0	2·28	2·53	2·18	0·99	0·85
3d	Näsijärvi	75	1·0	3·11	3·20	2·78	1·16	
4	Suolijärvi	44	0·9	3·86	3·87	2·82	1·78	
5a	Suonukkalampi	31	1·0	2·93	3·69			
6	Vihmas.järvi	23	0·7	5·26	8·84			
7_1	Inari	27	0·4			5·14		1·77
8	Melkutin	43	1·0		6·84		2·47	1·94
9a	Vuohijärvi	31	0·8	7·89	6·49	4·31	3·29	3·15
10	Mutkajärvi	16	0·2	8·47				

The variations in the activity levels of fish in the same lakes during 1962–5 are presented in Table III. The maximum values in fish were reached in 1964 or 1965, i.e. from 1 to 2 years after the maximum fallout.

Table III. ^{137}Cs *levels in the lakes under study during 1962–5 (relative amounts)*

	1962	1963	1964	1965
^{137}Cs in fish	0·7	1·0	1·6	1·6
^{137}Cs in fallout	1·0	2·0	1·2	

Until 1964 the ^{137}Cs contents of fish were sharply increased. Because of the long food chain and rather long biological half-times of ^{137}Cs in several fish species, the maximum body burdens in fish have been reached considerably after the maximal fallout. The limnological character of the lake seems to affect the rate of change of the ^{137}Cs content of the biota. In oligotrophic lakes slightly higher ^{137}Cs body burdens in the same fish were found in 1965 than in 1964, in the eutrophic lakes the maximum burdens were found in 1964. In oligotrophic lakes ^{137}Cs evidently remains a longer time in circulation in the biokenosis than in eutrophic lakes. The reason for this may be a greater content of clay particles which adsorb ^{137}Cs, greater sedimentation, lesser depth and smaller water volume in the eutrophic lakes. The bottom silt absorbs ^{137}Cs efficiently (cf. Clanton[(5)]). ^{137}Cs pollution is accentuated in two ways in oligotrophic lakes. The enrichment of ^{137}Cs in the biota is efficient because of the low K-content and the contents remain longer high. The long biological half-times of ^{137}Cs in fish—in perch the average is over one year in natural conditions—effect during the longer pollution times continuous increase of the body burdens of fish.

Maximum activities in 1965 were noticed in a lake (9b) which had not been studied previously; the activity of perch was 26·3 nCi/kg, that of roach 6·3 nCi/kg and that of whitefish 3·5 nCi/kg.

The ^{137}Cs content of zooplankton and aquatic plants is similarly related to the K-content and conductivity of water as that of fish (Tables IV and V). The species of the plankton samples in 1964

Table IV. Radiochemical analyses of plankton samples 1964–5

Lake no.	Date	Dry wt. % of fresh wt.	Ash wt. % of dry wt.	^{137}Cs (pCi/l.)	^{137}Cs (pCi/g dry wt.)	K mg/g dry wt.	^{137}Cs (nCi/g K)	Phytoplankton % of plankton
				1964				
1	17·7	2·90	15·6	45	1·51	17·3	0·09	
2	13·7	3·36	15·8	105	3·12	18·8	0·17	
3a	18·9	4·38	13·3	180	4·08	15·2	0·27	5
3d	25·6	2·15	24·8	250	13·2	10·7	1·23	25
4	13·7	7·80	19·5	120	16·0	11·4	1·40	25
7_1	20·7	2·73	12·1	460	16·6	11·4	1·45	10
8	6·9	5·62	5·0	730	11·9	9·7	1·22	
9a	11·8	3·75	13·5	600	15·9	12·7	1·25	
				1965				
1	9·9	3·17		50	1·48	55·1	0·003	
2	8·9	2·49		110	4·17	8·6	0·48	35
3a	10·9	4·11		90	1·97	20·9	0·09	5
3b	20·7	4·43		260	5·29	28·5	0·19	
3d	16·9	4·35		350	9·25	21·5	0·43	
4	28·7	2·84		440	9·05	23·9	0·38$_5$	
8	23·6	0·42		120	27·22	14·5	1·88	
9b	30.7	5·48		360	16·86	19·1	0·88	

Table V. ^{137}Cs content of horse-tail (Equisetum fluviatile) *during 1963–5*

Lake no.	Lake	Conductivity (mho, 18°C)	K (mg/l.)	1963 nCi/kg dry wt.	1963 nCi/g K	1964 nCi/kg dry wt.	1964 nCi/g K	1965 nCi/kg dry wt.	1965 nCi/g K
1	Niemenjärvi	85	3·5	2·6	0·08			1·9	0·15
2	Kytäjärvi	72	1·8	3·4	0·12	2·3	0·10	1·1	0·05
3a	Pyhäjärvi	71	2·4			3·7	0·16		
3b	Ilmoilanselkä	58	1·7					1·9	0·06
3c	Päijänne	47	1·0			10·8	0·27		
3d	Näsijärvi	75	1·0			8·9	0·43	6·7	0·40
4	Suolijärvi	44	0·9			4·9	0·17		
6	Vihmas.järvi	23	0·7			35·0	0·98		
9a	Vuohijärvi	31	0·8			44·8	2·03		
9b	Keritty	26	0·6					16·9	0·84
10	Mutkajärvi	16	0·2			76·1	2·11		
10a	Akulampi	15	0·4					92·5	3·40

are given in the paper by Jaakkola *et al.*[6] In Table V the exceptionally high ^{137}Cs-content in one sample of horse-tail is noticeable. This value exceeds even those of lichens.

The elucidation of the total scheme of ^{137}Cs in lakes presupposes a knowledge of the food chains and successive analyses of the ^{137}Cs-content of the different links in the food chain. This requires extensive limnological and radiochemical basic research.

When the activity level of fish in one lake is known for two given times—with a span of 1–3 months—and the biological half-time of the species in the water temperatures observed is known, the amount of ^{137}Cs obtained by fish per day can be calculated from the following equation:

$$A_t = A_0 e^{-kt} + \frac{pa}{k}(1 - e^{-kt}),$$

where A_t is the whole body retention of the fish at time t, nCi/kg fresh wt.; A_0 is the whole body retention of the fish at time $t = 0$, nCi/kg fresh wt.; k is the rate constant of the "slow" component of excretion of ^{137}Cs, d^{-1}; a is the average daily intake of ^{137}Cs, nCi per kg fresh wt, d^{-1}; p is the fraction of a single intake of ^{137}Cs excreted with the "slow" rate k.

When, in addition, the quality and activity of the food of the fish species is accurately known, it can be calculated from the value of a how much food the fish have eaten in a day. The fish obtain most of their radiocaesium in food, as the absorption through gills seems to be small compared with the intakes in the diet. This problem is under detailed study at the moment. To give an example of the calculations:

9 June 1964	7·89 nCi/kg $= A_0$
11 August 1964	7·37 nCi/kg $= A_t$

$$t = 63\,d$$
$$p = 0{\cdot}9$$
$$k = \frac{ln\,2}{200} d^{-1}$$

The calculation gives as the average intake of ^{137}Cs per day for the perch 22·8 pCi, d^{-1}. The activity of zooplankton was on 11 August, 15·9 pCi/g dry wt. Hence, the average daily intake of food for small perch in Vuohijärvi lake was 1·27% as dry weight of plankton per kg of fish weight (fresh).

In Table VI the intake of ^{137}Cs and consumption of food, calculated in terms of zooplankton, has been calculated according to the above example for the roach (20–25 cm, 6–11 *y.*) of some lakes. For the slow component a biological half-time of 100 days has been used (Häsänen *et al.*, this Symposium[4]). The annual growth of roach in each lake was determined on the basis of scale samples. The calculated food intake is directly proportional to the additional growth, even though the correlation in this case is not good. This is in part probably due, for instance, to the fact that the calculated food intake does not exactly correspond to the actual intake, since plankton samples were collected from each lake during one period only, and roach also eats bottom animals and parts of aquatic plants. The main purpose of the table is to illustrate how the activity levels of fish and food can be applied to calculate the daily intakes of ^{137}Cs and of food by fish, when the biological half-time of Cs in the fish species is known. Not until all the above-mentioned factors are known, can an elucidation of the total picture of the behaviour of ^{137}Cs in an ecosystem be attempted.

At the same time, fallout measurements can be used in limnology to investigate the food intake of fish, which would otherwise, e.g. through stomach analyses, be very laborious and difficult to accomplish.

Table VI. ^{137}*Cs in roach and its food in summer 1964*

Lake no.	Lake	Date (1964)	Conductivity (mho)	K (mg/l.)	^{137}Cs in roach, (nCi/kg fresh wt.)	^{137}Cs in plankton (pCi/g dry wt.)	^{137}Cs in food (pCi/day)	Food (% of wt. of fish)	Growth of fish (cm/y)
1	Niemenjärvi	21·5	85	3·5	0·19	1·5			
2	Kytäjärvi	14·7	72	1·8	0·25	3·1	2·7	0·8	2·5
		28·1			0·30				
3a	Pyhäjärvi	5·6	71	2·4	0·66				
		19·9			0·51	4·1	2·9	0·7	2·5
3c	Päijänne	2·7	47	1·0	0·99				
3d	Näsijärvi	24·6	75	1·0	1·16	13·2	9·6	0·7	2·5
		28·8			1·19				
4	Suolijärvi	16·5	44	0·9	1·53				
		14·7			1·78	16·0	18·4	1·1	2·8
8	Melkutin	25·5	43	1·0	2·51				
		6·9			2·47	11·9	20·8	1·8	2·6
9a	Vuohijärvi	9·6	31	0·8	3·29				
		14·8			3·83	15·9	36·9	2·3	2·8

Aquatic animals, with the exception of water fowl and aquatic mammals are cold-blooded. Hence, in all investigations involving aquatic animals the particular temperature of the water and also that of the different layers of water should always be taken into consideration, since, generally, the metabolism of aquatic animals (intake of food, respiration, excretion, exercise, etc.) is, within certain limits, directly related to the prevailing temperature; even though the optimum of some species is reached at a low temperature, these belong to the minority.

Another reason which often makes it impossible to apply results obtained elsewhere is the fact that no analyses of the water where the experiments were carried out or the samples were taken from are reported. Since the enrichment of ^{137}Cs and, viz., concentration factors are decisively affected by the K-content and possibly to a small extent even by other ions in the water, the conditions of existence in different waters where the electrolyte concentrations are different are not to be compared.

We are greatly indebted for financial aid from the U.S. Department of Health, Education and Welfare, Division of Radiological Health, Public Health Service, through its Grant RH-00307.

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Reprinted from
RADIOECOLOGICAL CONCENTRATION PROCESSES
Proceedings of an International Symposium held in Stockholm 25–29 April, 1966
PERGAMON PRESS — OXFORD & NEW YORK — 1966

BIOLOGICAL HALF-TIME OF ^{137}Cs IN THREE SPECIES OF FRESH-WATER FISH: PERCH, ROACH AND RAINBOW TROUT

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INTRODUCTION

Investigation of radioactivity of fresh-water fish in Finland during 1962–64 showed that ^{137}Cs is the only artificial long half-life nuclide present in easily measurable amounts in the flesh of fish. Concentrations up to 20 nCi/kg fresh weight—higher than in any other man's food except reindeer meat—were found in some fish samples in 1963 but great differences between species were noticed [1, 2]. Also, the levels were widely different in limnologically different lakes.[2] Since fresh-water fish is an important dietary item in many countries, the studies were expanded in 1964 to elucidate the different factors playing a role in the accumulation of ^{137}Cs in fish. These factors are discussed in another paper of this Symposium.[3] In addition to the food of the fish and the cation concentration in the water, the speed of excretion of ^{137}Cs plays an important role.

REVIEW OF LITERATURE

The rate of excretion of ^{137}Cs is known for a number of animal species. It usually follows a two-exponential equation: smaller fraction, typically 10–20%, shows a short biological half-time from a part of a day to a few days; the remaining bulk showing a many times longer biological half-time varying from a few days to a hundred days.[4] Of the excretion rates of ^{137}Cs in fish rather little is known, however. Carefully searching the literature we have found only the following scanty information on this subject:

Ichikawa[5] reports for salmon the biological half-time of ^{137}Cs between 5 and 10 days; Rudakov [6] gives for the Crusian carp (*Cyprinus* sp.) a value of 10–15 days. From the data published by Williams and Pickering[7] for small (2 g) bluegill fingerlings (*Lepomis macrochirus* Rafinesque) one can estimate for the fast component of excretion approximately 3–4 days, for the slow component about 40 days. The fast component represented about 88% of total excretion but cannot be accurately estimated because of the feeding technique used. Scott[8] reports for the brook trout (*Salvelinus fontialis*) 47 days, Nelson and Early[9] for blue gills (*Lepomis macrochirus*) 40 days, and Kevern *et al.*[10] for the carp's (*Cyprinus carpio*) slow component of excretion half-times of 98 days at 20°C and 174 days at 12·5°C. In several of the above studies the data are incomplete. Furthermore, some of the publications we have not yet in original form. It is not always evident from the available data which of the components, fast or slow, is in question, nor how great a proportion of the total excretion it represents. The size or age of the fish and the water temperature are usually not given. No information on half-times in fish species most common in our country could be found in the literature.

PRESENT STUDIES

Determinations of biological half-times in fish were started in our laboratory in summer 1964. The first experiment of 6 months' duration was carried out in aquaria with 150 small perch (*Perca fluviatilis* L.) of 6 months of age at the beginning of the study. Labelling was given in this experiment by keeping the fish for one hour in water containing 0·8 mCi carrier-free ^{137}Cs. For the slow component 200 $\pm$ 12 days and 83% were obtained at 15°C in tap water (250 mho) dechlorinized by

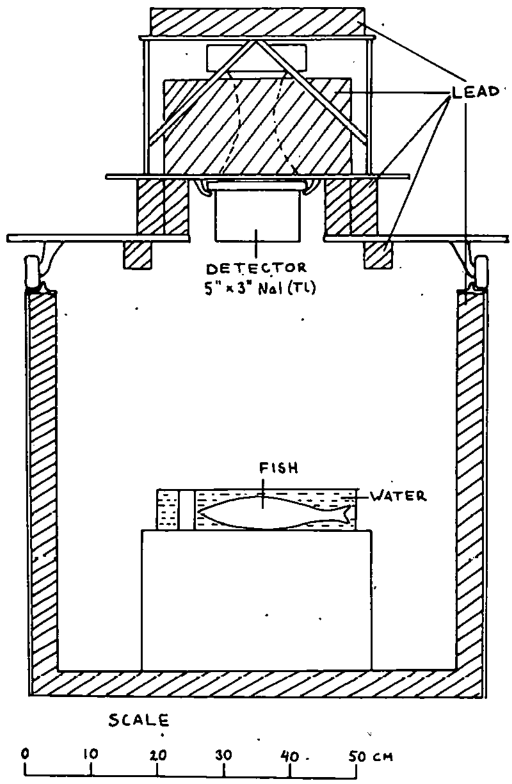

FIG. 1. Arrangement for "whole body counting" of live fish. The lead shield is 8 cm around the detector, 4 cm elsewhere, and weighs 1800 kg. It is located in a covered truck. 250 nCi ^{137}Cs at a distance of 42 cm gives 1170 cpm net within the ^{137}Cs-photopeak channel (BG is 200 cpm).

active charcoal.[11] The biological variation of the excretion rate between individual fish was considerable, one standard error being 24%. As it was not possible to carry out the studies with larger fish on a sufficient scale at the laboratory, they were continued in spring 1965 at the Kytäjä fish hatchery by keeping labelled fish in large cages of nylon net in the Suolijärvi lake (conductivity 55 mho). In this paper we report the results obtained with ^{137}Cs for the perch (*Perca fluviatilis* L.), roach (*Leuciscus rutilus* L.) and rainbow trout (*Salmo iridaeus*). Perch and roach were caught from the lake, the trouts bought from the hatchery. The fish were accustomed to feeding already before labelling them. Ground fish, ground liver or commercial fish food was given. The labelling was made either by giving to each fish *per os* a precisely known amount of carrier-free ^{137}Cs solution in a small (*ca.* 4 × 8 mm) gelatine capsule, or by injecting into the throat an aliquot of ^{137}Cs-containing gelatine jelly, or by feeding to the fish labelled food. The way of labelling depended on the size and species of the fish and the kind of experiment. To the smallest rainbow trouts (0·3–0·5 y), which were measured in groups of 50, about 5 nCi/fish was given. 250 nCi ^{137}Cs per fish was given to the other fish, which were marked by a fin mark and measured individually. The "whole body" measurements of live fish were carried out in the mobile counter of our laboratory, which was modified for this purpose (Fig. 1). After the initial measurement the fish were maintained on practically inactive food and taken for a 2 min. measurement after intervals of days or weeks. The first measurements were made at the beginning of June, the last ones at the end of November when the remaining fish were removed into aquaria in our laboratory. From the beginning of June to the end of September the water temperature was 15 ± 5°C. The values reported in Table 1 were obtained in these conditions. At the beginning of October the water temperature rapidly decreased to about 5°C which made possible estimations of the effect of temperature on the rate of excretion.

Table 1. The biological half-time (slow component) of ^{137}Cs in perch, roach and rainbow trout at 15 ± 5°C. Conductivity of the water was 55 mho

Fish	Age (years)	No. of fish	Temp. (°C)	"Long" biol. half-time of ^{137}Cs % of total	Days
Perch					
Perca fluviatilis	2–3	16	15 ± 5	94	175
	3–6	12	15 ± 5	96	175
	6–8	3	15 ± 5	88	200
Roach					
Leuciscus rutilus	2–3	11	15 ± 5	94	55
	4–6	4	15 ± 5	93	85
	9–12	3	15 ± 5	91	100
Rainbow trout					
Salmo iridaeus	0·3–0·5	50	15 ± 5		25
	1–2	18	15 ± 5	66	55
	2–3	15	15 ± 5	76	80

RESULTS AND DISCUSSION

The results are presented in Table 1. They are also illustrated in Fig. 2, where results of measurements of a group of 11 roach are presented. For the "slow" component of perch, half-times of 175–200 days and 88–96% of total excretion were obtained. There seems not to be any clear age dependence as the earlier value, obtained in 1964 for the 6-months' old perch, was 200 ± 12 days, as mentioned above. In this earlier experiment the percentage of the fast component was higher (17%), possibly partly due to skin adsorption, as the labelling was given in water, not *per os* as in these later experiments. In roach the value of the "slow" component of caesium excretion varies at 15°C from 55 to 100 days depending on the age of the fish. The fast component represents 6–9% of total excretion (Fig. 2). In the rainbow trout, too, the value of the slow component, 25–80 days at 15°C depends on the age of the fish. The fast component, 24–34% of total excretion, is much bigger than that of the two other species.

As is seen from the results, the biological half-times vary largely with the species.

When the water temperature had decreased to about 5°C, the excretion rate of ^{137}Cs was clearly retarded. Decrease of 10°C in temperature increases the values of the slow component to about two- or three-fold. Studies, which are still going on in our laboratory, corroborate this result.

Compared with those of the earlier workers our results for perch, roach and rainbow trout seem to be in harmony with those of Scott for the brook trout, 47 days,[8] Nelson and Early for the bluegills, 40 days[9] and Kevern *et al.* for the carp, 98 days at 20°C and 174 days at 12·5°C.[10] This temperature dependence is very similar with our present results. The small half-times of Ichikawa and Rudakov evidently represent the fast component. This seems to be the case at least in Rudakov's experiments, as the excretion was only followed for 12 days. Species difference, different ion concentrations and temperatures and other factors may also have caused the difference.

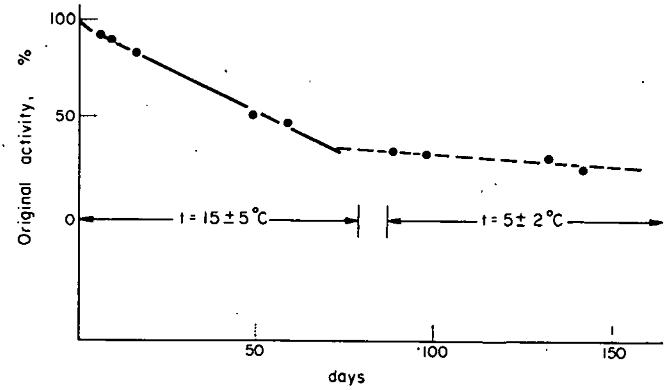

FIG. 2. Excretion of ^{137}Cs from roach (*Leuciscus rutilus*). Each point is mean of 11 fish, measured separately Age of the fish was 2 to 3 years.

Acknowledgement—This investigation was financed by the Division of Radiological Health, Bureau of State Services, U.S. Department of Health, Education and Welfare (Public Health Service Research Grant RH-00307), and by the Finnish Atomic Energy Commission. We are greatly indebted to the Kalamiesten Keskusliitto (Central Organization of Fishermen) for permitting us to use the facilities of the Kytäjä hatchery. Mr I. Vöry and Mr S. Takatalo have given technical assistance in the study.

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(*Reprinted from Nature, Vol.* 212, *No.* 5060, *pp.* 379–382, *October* 22, 1966)

GAMMA EMITTING RADIONUCLIDES IN SUBARCTIC VEGETATION DURING 1962–64

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INVESTIGATIONS of environmental radioactivity in Finnish[1,2] and Swedish[3] Lapland and in Alaska[4,5] have revealed conspicuous food chains leading from vegetation to cattle—reindeer and cows—and man. The most important of these food chains starts with lichens and ends in Lapps, who have body burdens of caesium-137 thirty to forty times higher than other Scandinavians. Lichens take their nutrients directly from the air, grow very slowly and are the most important food of reindeer during the 6–7 months of winter.

There are few published data on the radioactivity of the first link of the chain, the arctic and subarctic vegetation. In addition to two papers from this laboratory[6,7], studies from Sweden[8] and Alaska[9,10] exist. This article reports the results of analysis of gamma emitting radionuclides, mainly caesium-137, from Finnish Lapland and, for comparison, from some other parts of Finland, undertaken over 3 years of high fall-out, from 1962 to 1964. Altogether in this investigation, 114 samples were separately analysed and thirty-two different plant species studied. Emphasis was placed on analysis of species important as fodder for reindeer and cows.

In winter, the reindeer feed almost entirely on lichens (85–90 per cent by weight), mainly *Cladonia* species, whereas during the summer they feed almost entirely on vascular plants. Reindeer also eat a small quantity of vascular plants in winter, and perhaps the most important of these is *Deschampsia flexuosa*. In spring and autumn especially reindeer also dig up rootstocks of *Menyanthes trifoliata*, *Potentilla palustris* and some *Carex* species (*C. rostrata*, *C. aquatilis*, *C. lasiocarpa*), and, for a short period in the autumn, they consume fungi[11,12]. The very varied summer diet includes numerous marsh plants, leaves of birch, willow and *Vaccinia* species, but also small quantities of lichens (about 5–10 per cent).

Lapland, where most of the samples were collected, is that part of Finland north of the Arctic circle (between 67° and 70° N.). It is rather elevated, mostly 200–400 m above the sea level, with numerous hills, often between 500 and 700 m. The rock is mainly granite, gneiss or granulite. The soil is half moraine (97 per cent of mineral soils) and half peat. The average annual temperature is −1° to −2° C, with −11° to −13° in January, +11° to +13° in July. The rainfall is 400–450 mm/yr. The vegetation is partly coniferous (forest Lapland) and partly poor heath birch forests rich in lichens (in the most northerly part)[13].

For comparison, samples of the same species were collected from central and southern Finland. These areas belong to the coniferous zone, have an average annual temperature from 2° to 5° C and an annual rainfall from 600 to 700 mm. In addition to the terrestrial plants, some waterside and aquatic plants were collected in 1963 in connexion with an investigation of hydrospheric radionuclide food chains[14].

Each sample was formed by combining a number of smaller samples collected from an area of about 0·5–1 hectare. The fresh weight of the bulked sample was 1–5 kg. The lichen samples mainly represent an area of 0·25–1 m², and it is therefore possible to estimate the amount of fall-out on each unit area. The samples were dried in the laboratory at 100°–105° C. They were then ground and the caesium-137 content was determined using a γ-spectrometer, either directly or after chemical separation.

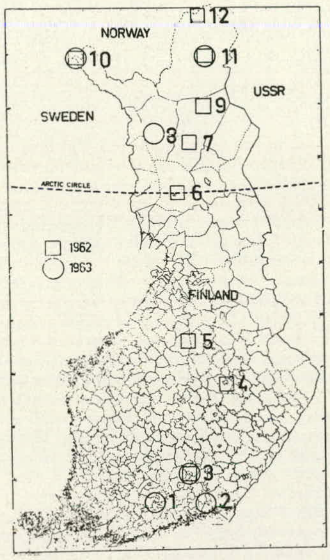

Fig. 1. Places of collection (areas 1–12) of plant samples for the analysis of radionuclides. Lapland is to the north of the Arctic circle.

The 1962 samples were analysed with a γ-spectrometer in 1964 so that short-lived nuclides would no longer interfere.

An *SKT* pulse height analyser with 512 channels was used with a 5 × 3 in. sodium iodide (thallium) crystal (without a well) as the detector. The energy range used in the measurements was 0·15–1·8 MeV, and the photopeaks of five nuclides—antimony-125, ruthenium-106 and rhodium-106, caesium-137, manganese-54 and potassium by potassium-40—were recorded in this range. The system was calibrated for each of these nuclides and the contribution of each nuclide in the energy range of the others was established. IAEA or Amersham absolute or reference standards were used for the calibration, and potassium chloride (Merck) for calibration of the potassium nuclides. For antimony-125, only the Amersham product *ACS* 1 was available, and its efficiency was therefore calculated from the disintegration scheme[18].

The total gamma spectra of the different nuclides were analysed by the stripping method, so that with the overlapping gamma peaks (caesium-137, ruthenium-106 and rhodium-106, antimony-125) a "trial and error" method was used, and for ruthenium-106 and rhodium-106 a narrow energy range in the middle of the photopeak. The accuracy of the results on caesium-137 was controlled by analysing some of the samples radiochemically. The results agreed within the limits of the counting statistics.

The energy ranges, efficiencies and backgrounds used in the measurements are given in Table 1.

Table 1

Element or nuclide	Energy range (MeV)	Efficiency (c.p.m./nc.)	Background (c.p.m.)
Potassium	1·37–1·56	8·71*	26·4
Manganese-54	0·78–0·90	156·8	36·4
Caesium-137	0·60–0·72	156·1	49·4
Ruthenium-106 + rhodium-106	0·48–0·54	23·6	32·7
Antimony-125	0·40–0·46	81·0	31·8

* Value for potassium in c.p.m./g potassium.

The average statistical error of the measurements (one standard deviation) for the different nuclides was

	K (%)	^{54}Mn (%)	^{137}Cs (%)	^{106}Ru (%)	^{125}Sb (%)
Lichens	25	6	1	8	18
Other plants	6	5	3	30	30

The 1963 samples were analysed by first separating caesium-137 chemically and then measuring the resultant preparation with a well-type crystal and a single channel analyser.

We used a modification of the AMF method of Van der Stricht[15]. A 50–100 g ground plant sample was extracted for 2–3 h in boiling 3 normal nitric acid into which 2 mg of caesium carrier was added. The plant extract was filtered and the filtrate concentrated through evaporation. A mixture of freshly prepared ammonium molybdophosphate (AMF) with Whatman cellulose powder was added to the concentrate. The slurry was mixed for 1 h with a magnetic stirrer so that the caesium-137 was adsorbed by the AMF. The pulp was centrifuged, rinsed with methanol, packed into a plastic tube and measured with a well-type crystal and a single channel analyser for 100 min. The efficiency of the system for caesium-137 was about 10 per cent, the energy range used was 0·61–0·71 MeV, and the statistical accuracy fluctuated between 1 and 10 per cent, being generally 2–3 per cent. A relatively small statistical error was achieved, because of the low and very stable background (about 10 c.p.m.).

This method is highly specific for caesium-137 (only a large excess of zirconium-95–niobium-95 interferes slightly). A drawback is that the yield cannot be determined for individual analyses. In a series of spiked known trials the yield was found to be 95 ± 3 per cent. In most cases, the extracted plant pulps and the nitric acid solutions from which caesium-137 had been removed were both measured with a multichannel analyser to check the losses of caesium-137. No other nuclides were noticed in the AMF preparation (Fig. 2).

Curve *A* is the spectrum of such a nitric acid solution from which caesium-137 has been separated, curve *B* is the spectrum of the AMF preparation, and curve *C* is the spectrum of the plant pulp extracted with nitric acid. The accuracy of the caesium determinations using this method is about ± 10 per cent.

Fifty-one samples collected in 1962 were analysed. Of these, eighteen were perennial plants, lichen or moss (Table 2), fourteen birch, eight willow samples and eleven annual vascular plants (Table 3). Of the latter, seven were samples of *Vaccinium* species and two of different wild grasses. In Table 3 the samples from Lapland and other parts of Finland are combined when calculating averages, because marked differences were not found between samples of the same species collected from different parts of the country.

Examination of the results shows that the perennial plants, lichen, moss and *Alectoria*, and the annual horsetail, form a "high activity group". The caesium-137 content of the samples of *Cladonia alpestris* varies between 17–27 nc./kg (dry weight), the mean being 22·4 nc./kg (dry weight). The average dry weight of 1 m² is 620 g, so that the caesium-137 content of the 1962 samples is about 15 nc., which equals 15 mc./km².

Table 2. RADIONUCLIDES IN LICHENS AND MOSS IN DIFFERENT PARTS OF FINLAND DURING 1962

Name of species	Area No.	K (g/kg) (Dry weight)	^{137}Cs (nc/kg) (Dry weight)	nc ^{137}Cs / gK	^{54}Mn (nc/kg) (Dry weight)	^{106}Ru (nc/kg) (Dry weight)	^{125}Sb (nc/kg) (Dry weight)
Cladonia alpestris (lichen) Lapland	10	3·6	19·3	5·4	3·6	14·3	1·0
	6	2·3	25·3	11·0	6·0	25·5	1·8
	7	4·6	22·8	5·0	6·0	27·6	1·1
	9	5·6	28·1	5·0	5·4	25·5	1·6
	9	4·3	23·2	5·4	4·7	19·2	1·9
	11	1·3	20·6	15·9	4·6	22·1	1·4
	11	3·3	25·9	7·8	5·3	29·7	1·8
	12	3·5	25·4	7·3	5·9	26·7	1·7
Average		3·6	23·8	6·6	5·2	23·8	1·8
Cladonia alpestris Middle Finland	5	3·9	19·4	5·0	5·6	24·4	1·7
	5	3·5	14·7	4·2	4·2	25·7	1·4
	4	5·2	19·3	3·7	5·2	24·1	2·0
Average		4·2	17·8	4·3	5·0	23·4	1·7
Cladonia alpestris Southern Finland	2	3·4	22·9	6·7	5·1	24·0	1·4
	2	3·1	20·9	6·7	5·0	36·7	0·8
	2	4·6	21·9	4·8	4·8	24·2	1·3
	3	4·7	25·6	5·4	6·8	27·0	1·6
Average		4·0	22·8	5·9	5·4	28·0	1·3
Average all		3·8	22·4	6·6	5·2	24·8	1·5
Stereocaulon paschale (lichen) (Lapland)	9	3·6	18·1	5·0	3·9	24·8	1·3
Alectoria sp. (moss) (Lapland)	7	7·0	16·2	2·3	5·8	33·4	2·5
Calliergon stramineum (moss) (Lapland)	9	47·7	15·5	0·33	10·9	12·9	

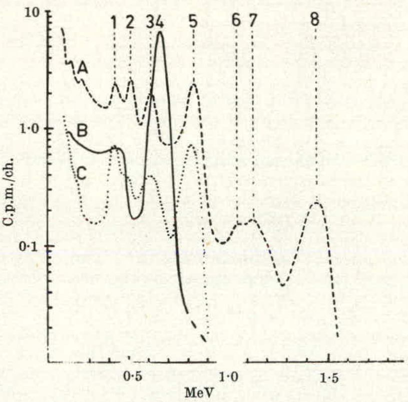

Fig. 2. Gamma spectra illustrating the absorption of caesium-137 from nitric acid extract of vegetation on an ammonium-molybdophosphate (AMF) precipitate. *A*, Nitric acid extract after removal of caesium-137; *B*, AMF precipitate with the adsorbed caesium-137; *C*, plant material after extraction with hot nitric acid. The photopeaks numbers 1–8 shown represent the following nuclides and energies: 1, ^{125}Sb (0·43 MeV); 2, ^{106}Ru + ^{106}Rh (0·51 MeV); 3, ^{125}Sb (0·60 MeV), ^{106}Ru + ^{106}Rh (0·62 MeV); 4, ^{137}Cs (0·66 MeV); 5, ^{54}Mn (0·84 MeV); 6, ^{106}Ru + ^{106}Rh (1·05 MeV); 7, ^{106}Ru + ^{106}Rh, sum peak (1·14 MeV); 8, ^{40}K (1·46 MeV).

On the other hand, the caesium-137 content of the annual plants, other than horsetail, is only a fraction of that of the plants already mentioned. No noticeable differences were observed in the levels of activity of the different species. The annual plants analysed seem to have no exceptional enrichment in content of any of the nuclides analysed.

Sixty-three samples taken in 1963 were analysed for caesium-137 with the so-called AMF method as already described. The results are given in Tables 4 and 5.

On examination of the min–max values, it is clear that the variation in the caesium-137 content in a terrestrial annual plant was only a few tens per cent (Table 4), whereas the variation in the waterside and aquatic plants (*Carex*, *Equisetum*) was up to ten times as great

Table 3. RADIONUCLIDES IN VASCULAR PLANTS IN DIFFERENT PARTS OF FINLAND DURING 1962
(Samples are from Lapland, if not marked otherwise)

Name of species		Area No.	No. of samples	K (g/kg) (Dry weight)	^{137}Cs (g/kg) (Dry weight)	nc. ^{137}Cs / gK	^{54}Mn (nc./kg) (Dry weight)	^{106}Ru (nc./kg) (Dry weight)	^{125}Sb (nc./kg) (Dry weight)
Betula (birch)									
ortuosa		9–12	7	9·4	2·3	0·24	2·3	11·1	1·5
nana		9, 10	2	7·3	2·1	0·31	2·1	9·6	1·1
verrucosa		7	1	7·8	2·6	0·33	2·4	13·2	1·9
	*MF**	4	1	10·4	2·7	0·26	1·8	13·6	1·7
	SF†	2	1	9·1	3·4	0·37	3·3	15·5	2·1
pubescens	*MF*	5	1	11·6	1·0	0·09	1·8	8·3	1·7
	SF	3	1	8·8	3·5	0·39	3·4	12·1	1·5
	Average		14	9·1	2·4	0·27	2·4	11·4	1·6
Salix sp. (willow)		9–11	6	12·0	2·1	0·19	1·2	6·6	1·0
,,	(*MF*)	5	1	12·7	2·0	0·16	2·7	13·2	1·3
	(*SF*)	2	1	13·8	2·6	0·19	1·8	9·0	1·5
	Average		8	12·3	2·2	0·18	1·5	7·7	1·3
Vaccinium myrtillus (whortleberry)		10, 11	3	8·2	3·2	0·39	1·8	6·1	0·8
,,	(*MF*)	4, 5	2	9·5	5·4	0·60	3·3	13·0	2·7
	Average		5	8·7	4·1	0·47	2·4	8·9	1·8
,, *uliginosum* (bog bilberry)		6	1	8·1	1·7	0·21	0·8	2·7	0·4
,, *Vitis idaea*		11	1	5·7	3·9	0·68	1·3	6·7	0·8
Poa pratensis (june grass)		11	1	14·0	1·0	0·09	0·6	—	—
Festuca rubra (red fescue)		11	1	21·8	4·9	0·23	—	0·6	0·6
Equisetum (horse-tail)									
fluviatile		11	1	40·6	18·7	0·46	—	—	—
silvaticum		11	1	33·4	16·8	0·50	6·6	9·3	0·8

* *MF*, Middle Finland. † *SF*, Southern Finland.

within the same species (Table 5). This variation was mainly due to differences in the potassium and sodium concentrations in the water (Table 6). Also, this situation probably shows that the terrestrial plants acquired the chief part of their caesium-137 in summer 1963 through their aerial parts, as no effect of the soil on the caesium-137 content can be observed.

The purpose of the analyses of water plants was to find whether there is a correlation between the caesium-137 content of a specific plant and that of the general biota of the same lake. For example, the caesium-137 content of *Equisetum fluviatile* and of fish seems to correlate in many cases. If a suitable general "indicator" plant is found, analyses of such a plant will make it possible to estimate the level of activity of the biota in general. *Equisetum* seems to be promising in this respect. This limnological relationship has been treated in detail elsewhere[14].

A comparison of the analyses of tree leaves during 1962 and 1963 reveals that the fall-out during the summer of 1963 was about twice that in the summer of 1962. The analyses of lichen show that the increase of caesium-137 from summer 1962 to summer 1963 was 9 mc./km^2.

Table 4. CAESIUM-137 IN TERRESTRIAL PLANTS IN LAPLAND DURING 1963

Name of species	Area No.	No. of samples	^{137}Cs nc./kg (dry wt.)	Min–max
Cladonia alpestris (lichen)	11	1	37·1	
Betula (birch)				
tortuosa	10, 11	2	5·5	(4·5–6·4)
nana	8	1	4·7	
pubescens	8, 11	6	4·3	(3·9–5·8)
		9	4·6	
Salix (willow)				
lapponum	8, 10, 11	3	6·1	(5·8–7·2)
phylicipholia	8	2	4·2	(4·1–4·2)
glauca	8	3	3·8	(3·4–4·2)
		8	4·7	
Deschampsia flexuosa (wood hair grass)	8, 10, 11	8	5·2	(3·6–6·7)
Potentilla palustris (five finger)	8, 10, 11	3	7·9	(4·5–10·9)
Eriophorum vaginatum	8, 10	2	8·4	(7·6–9·2)

Table 5. CAESIUM-137 IN AQUATIC PLANTS IN FINLAND DURING 1963
(Samples are from Lapland, if not marked otherwise)

Name of species	Area No.	No. of samples	^{137}Cs (nc./kg, dry wt.)	(Min–max)
Carex (sedge)				
rostrata	8	5	6·2	(1·5–12·2)
vesicaria	10	1	17·7	
vesicaria (*SF*)*	1	1	4·0	
aquatilis	8	2	7·9	(5·8–10·0)
acuta	11	2	0·8	(0·2–1·4)
lasiocarpa	8	1	6·0	
Average		12	6·4	
Equisetum (horse-tail)				
fluviatile	8, 10, 11	5	15·7	(7·8–33·3)
fluviatile (*SF*)	1	4	4·2	(2·7–7·5)
Average		9	10·6	
silvaticum	11	1	5·3	
Myriophyllum (parrot's feather) (*SF*)	1	1	5·4	
Typha latifolia (cat tail) (*SF*)	1	1	0·8	
Menyantes trifoliata (buckbean)	8, 11	3	6·4	(2·4–14·1)
(buckbean) (*SF*)	1	2	3·7	(2·7–4·7)
Average		5	6·0	
Sparganium simplex (bur reed) (*SF*)	1	4	1·8	(0·9–3·1)
Scorpidium scorpioides (bottom moss) (*SF*)	1	1	6·3	

* *SF*, Southern Finland.

On the other hand, the amount of caesium-137 in the fall-out during this period also can be calculated from the known fall-out of strontium-90 (see ref. 16) because the ratio of these nuclides in the test period 1961–62 is known to be 1·6. A calculation gives 7·5 mc./km^2 for caesium-137 in 1962 and 14 mc./km^2 in 1963 between 0–80° N., which corresponds to about 11 mc./km^2 for the period July 1963–July 1964. This value is slightly higher than the observed increase in lichen. This shows that caesium-137 is retained almost quantitatively by the lichen.

Table 7 presents the results of the measurements of four radionuclides in a species of birch and in lichen,

Table 6. CAESIUM-137 CONTENT OF *Equisetum fluviatile* AND THE ELECTROLYTIC CONDUCTIVITY OF WATER IN FIVE LAKES IN FINLAND, 1963

Name of lake	Area No.	^{137}Cs nc./kg (dry wt.)	Conductivity (mho, 18° C)
Niemenjärvi	1	2·7	77
Kytäjärvi	1	3·0	72
Mustalampi	1	7·5	40
Inarinjärvi	10	7·8	27
Kilpisjärvi	11	17·8	24

the samples being collected at the same locations at intervals of 1 year. The γ-spectrometric analyses were carried out in August 1964, and the results were corrected to the date of collection of the sample.

These results for single samples show that the caesium-137 fall-out in summer 1963 was four times that in 1962, and in 1964 twice that in 1962. The caesium-137 content of lichen had increased from July 1962 to July 1963 by 80 per cent, and from July 1963 to July 1964 by 85 per cent.

Other analyses of the 1964 samples show that the level of caesium-137 in annual plants had dropped to about the 1962 level. They also show that the fall-out in Lapland during 1964 was somewhat higher than in southern Finland, evidently because of an unusually rainy summer in Lapland. The rainfall from May 1 to August 31, 1964, in Lapland was 240 mm, in southern Finland it was 140 mm; in normal years it is lower in Lapland.

Table 7. FOUR γ-NUCLIDES IN LEAVES OF *Betula tortuosa* AND IN *Cladonia alpestris*, YEARS 1962, 1963, 1964 (Location 69·2° N., 27·2° E.)

Time of sampling	^{137}Cs nc./kg (dry wt.) Birch	^{137}Cs Lichen	^{54}Mn nc./kg (dry wt.) Birch	^{54}Mn Lichen	^{106}Ru nc./kg (dry wt.) Birch	^{106}Ru Lichen	^{125}Sb nc./kg (dry wt.) Birch	^{125}Sb Lichen
July 1962	1·5	20·6	1·7	5·2	7·6	29·7	1·6	1·6
July 1963	6·4	37·1	15·3	19·7	32·8	49·8	6·2	3·9
July 1964	3·3	68·6	1·9	15·0	7·8	42·4	1·6	2·6

Table 8 shows variation within one summer period. The leaves of the same individual tree (*Betula pubescens*) were sampled at intervals of 1 month and analysed for caesium-137 and potassium. As can be seen, the caesium-137 content increased by about 50 per cent from June to August, but decreased in September. The fact that the potassium content remained constant until August but decreased in September probably indicates that caesium-137 is mobilized by the withering processes which are known to mobilize several nutrients, among them potassium, in the plants. Some leaching may also have taken place. Auerbach *et al.*[17] report somewhat similar results from studies of caesium metabolism in different trees.

Table 8. CAESIUM-137 AND POTASSIUM CONTENTS IN THE LEAVES OF THE SAME BIRCH (*Betula pubescens*) DURING SUMMER 1964 (Location 60·3° N., 24·8° E.)

	June	July	August	September
nc. ^{137}Cs/kg (dry weight)	1·2	1·7	1·8	1·5
gK/kg (dry weight)	10·2	10·9	10·7	9·2

Our results show that lichens take up caesium-137 from fall-out almost quantitatively and that they retain it for years. Uptake by the aerial parts of vascular plants was more efficient than uptake by roots in the years 1962 to 1963. No marked differences were observed in the activity of the same species growing in different soils. *Equisetum fluviatile* seems to be a suitable indicator plant to characterize the caesium-137 content of a freshwater biota.

This investigation was supported by grants from the Finnish Atomic Energy Commission and the U.S. Atomic Energy Commission. Dr. T. Ahti kindly helped us to identify the plant species.

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Reprinted from

PROCEEDINGS OF THE FIRST INTERNATIONAL CONGRESS OF RADIATION PROTECTION

held at Rome, Italy, September 5-10, 1966

PERGAMON PRESS - OXFORD & NEW YORK - 1968

BIOLOGICAL HALF-TIMES OF ^{137}Cs AND ^{22}Na IN DIFFERENT FISH SPECIES AND THEIR TEMPERATURE DEPENDENCE

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Abstract—Biological half-times of ^{137}Cs in 5 species of fish were determined by giving *per os* a precisely known dose (usually *ca.* 250 nCi) of ^{137}Cs in a gelatine jelly or in a tiny gelatine capsule and by whole body counting the fish, first daily, then weekly, in the Institute's mobile whole body counter. Experiments were continued for up to 6 months. Twelve experiments were carried out in the field in summer (May–October) and 16 in the laboratory, where it was possible to keep a constant temperature (from 6 to 20°C) in the aquarium.

The excretion of ^{137}Cs from fish follows a two-differential equation: the fast component (usually 5 to 10% but in *Salmo* 25 and in *Cyprinus* 50% of the amount administered) has a half-time of a few days, the slow component is about one order of magnitude longer. At 15°C the long component is for perch (*Perca fluviatilis*) 200 days, roach (*Leuciscus rutilus*) from 100 days (age 11 years) to 57 days (3 years). For the rainbow trout (*Salmo iridaeus*) the long component varies from 20 to 80 days depending on the age of the fish. The value for young fish (1 year, 20 days at 20°C) is increased to 36 days at 7–8°C. Crucian carp (*Cyprinus carassius*) of about 5 years of age has a half-time of 55 days at 20°C, 120 days at 10°C.

The biological half-times of ^{22}Na are much shorter, but the temperature dependence seems to be very similar to that of ^{137}Cs. For perch, half-times of ^{22}Na were 7 days at 20°C, 15 days at 10°C; for roach 7 days at 20°C, 11 days at 10°C; for burbot 30 days at 10°C, for the Crucian carp 10 days at 20°C, 25 days at 10°C.

Knowledge of the body burden and of the biological half-time make possible calculation of the daily intake of ^{137}Cs by fish in natural conditions.

INTRODUCTION

The excretion rate of ^{137}Cs is known for a number of animal species.[1] It usually follows a two-exponential equation: a smaller fraction, typically 10 to 20% shows a short biological half-time (TB_1) varying from part of a day to a few days. Evidently, this fraction mainly represents ^{137}Cs in the extracellular space. The remaining bulk shows a biological half-time (TB_2) many times longer, varying from a few days to one hundred days. This fraction evidently represents ^{137}Cs in the intracellular space and especially within the muscle cells. Knowledge of the biological half-time(s) is necessary for the quantitative treatment of the behaviour of ^{137}Cs (and any other nuclide having an exponential excretion rate) in organisms, which again is necessary for clear understanding of the behaviour of the nuclide in a foodchain.

Except for ^{55}Fe which cannot be measured[2] by ordinary thick crystal gamma spectrometry, ^{137}Cs is the only artificial long-lived nuclide present in easily measurable amounts in the flesh of fish. ^{90}Sr is also present in fish in considerable concentrations but it is mainly located in the bones, which are not eaten by man. The presence of ^{55}Fe has been recently shown independently by Jaakkola[3] in fresh water fish and Palmer[2] in ocean fish. Ocean fish may contain it in high concentration (max. 2 μCi/kg fresh wt. in salmon liver.[2] ^{137}Cs is found in fresh water fish in high concentrations, the highest value was in 1965 in the Finnish perch 26 nCi/kg fresh weight,[4] which is more than in any other food eaten by man except reindeer meat. Fish flesh is the primary source of ^{137}Cs for population groups consuming fresh water fish, with the exception of reindeer-herding Lapps and other peoples consuming mainly reindeer or caribou meat having 2 to 4 times higher maximal ^{137}Cs contents than the fresh water fish. Even for these peoples fish is usually the second source of ^{137}Cs in importance.[5] ^{137}Cs content of lake fish varies greatly in different waters according to the limnological type of the water,[4] but even in the same water there exist great differences in the ^{137}Cs content between various species of fish. These are partly due to differences in the diets of the fish, but an equally important cause is a different excretion rate of ^{137}Cs in the various fish species, as will be shown in this paper.

EXPERIMENTAL

The experimental technique has varied to some extent. The first experiment was carried out with 150 small perch, 6 months of age, weighing 1–1.5 g each, in an aquarium in the laboratory. In this experiment labelling was given externally by keeping the fish for 1 hr in water (electrolytic conductivity 250 mho, potassium 5 mg/l) containing 860 μCi carrier-free ^{137}Cs in 8 l. Each fish took up 1.8 nCi, 150 fish thus taking 0.27 μCi or 0.03% of the amount given. The concentration factor was 0.012. Then the fish were grown with inactive food in a 200 l. aquarium (conductivity 250 mho, potassium content 5 mg/l.) in slowly changing inactive water. The experiment was continued for 6 months taking samples of 15 to 25 fish for measurement with intervals from 2 days to several weeks.

In most other experiments each fish has been labelled individually by giving it a precisely known amount of ^{137}Cs (usually 250 or 500 nCi) orally in a tiny gelatine capsule (4 × 8 mm). Each fish was then marked by clipping different fins and measured alive in the Institute's mobile whole body counter (Fig. 1), first at one-day intervals, later less frequently.

In field experiments the fish were kept in large cages made of Japanese nylon net and placed in the oligotrophic Suolijärvi lake.[4] They were regularly fed commercial fish food or milled inactive fish. In laboratory experiments they were kept in aquaria of different sizes, up to 1 m × 2 m × 70 cm (depth). In some experiments, with quite young fish, the isotope was given orally by injecting an aliquot of ^{137}Cs-containing gelatine jelly into the oesophagus. In one experiment the isotope was given by feeding labelled food to the fish.

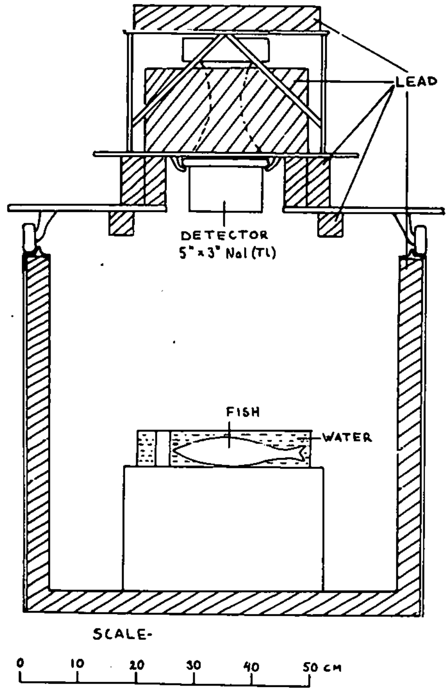

FIG. 1. Arrangement for whole body counting of live fish, initially labelled by an oral dose of 250 nCi ^{137}Cs. This activity gives 1170 cpm net within the ^{137}Cs photopeak channel at a distance of 42 cm. BG is 200 cpm. The lead shield is 4 to 8 cm thick and weighs 1800 kg.

As the fish in nature get the bulk of their ^{137}Cs in food, oral administration corresponds best to the natural conditions. In addition, a precise determination of the short component requires instantaneous administration of the isotope. Furthermore, the external labelling seems to give a higher percentage of the short component, probably due to partial adsorption on the surface of the fish (Table 1, line 1). Therefore, oral administration has been used in all experiments but the first.

Table 1. Biological Half-time of ^{137}Cs in Five Species of Fresh-water Fish
(F, Field experiment; L, Laboratory experiment)

Fish species	Type of expt.	Age of fish yr.	No of fish in expt.	Temp. °C	Fast comp. (TB_1) days	Fast comp. (TB_1) %	Slow comp. (TB_2) days	Slow comp. (TB_2) %
Perch	L	0.5–1*	150	18 ± 2		17	200	83
(*Perca fluviatilis*)	F	2–3	16	15 ± 5	12	6	175	94
	F	2–3	6	15 ± 5		6	220	94
	F	3–6	12	15 ± 5		4	200	96
	F	6–8	3	15 ± 5		10	220	90
Roach	F	2–3	11	15 ± 5		6	57	94
(*Leuciscus rutilus*)	F	4–6	4	15 ± 5		6	85	94
	F	9–12	3	15 ± 5		10	150	90
	F	2–3	11	5 ± 2			340	
Rainbow trout	L	0.5–1	7	20 ± 0.2			20	94
(*Salmo iridaeus*)	L	0.5–1	11	14 ± 1			19	90
	L	0.5–1	10	7 ± 1	3	26	34	74
	F	0.3–0.5	50	15 ± 5	5	25	25	75
	F	1–2	18	15 ± 5	5	34	55	66
	F	2–3	15	15 ± 5	7	24	80	76
	F	1–2	17	4 ± 1			≃ 150	
	F	2–3	15	4 ± 1			≃ 230	
Crusian carp	L	5	29	20 ± 0.2	2	50	55	50
(*Cyprinus carassius*)	L	5	28	8 ± 3	3	55	120	45
Burbot	L	5	1	8 ± 3	8	14	110	86
(*Lota vulgaris*)								

* Labelling given externally.

The *measurement* has been made with a multichannel analyzer at 42 cm distance from the 5 × 3 NaI(Tl) crystal (Fig. 1). With 250 nCi 1170 cpm net are obtained within the ^{137}Cs photopeak channel. With 250 to 500 nCi initial labelling and 2 to 4 min counting time a statistical accuracy (1 σ) better than 3% is obtained throughout the experiment of 2 × TB_2. This statistical error is small compared with the *biological* variance which is for individual fish 25%, and for a group of 15 fish 6% (1 σ) after external labelling and one TB_2 (unpublished). This is mainly due to differences of TB_2 between individuals of the same species.

RESULTS

The results for ^{137}Cs are presented in Table 1. Those for rainbow trout are also illustrated in Fig. 2. The points for TB_1, the fast component of the biological half-time, have been obtained by subtracting from the total retention the part due to the slow component, TB_2, obtained by extrapolating to zero in the usual way. At the beginning of October the water temperature decreased in 2 weeks from 13°C to 5°C; the value of TB_2 then increased to about 230 days.

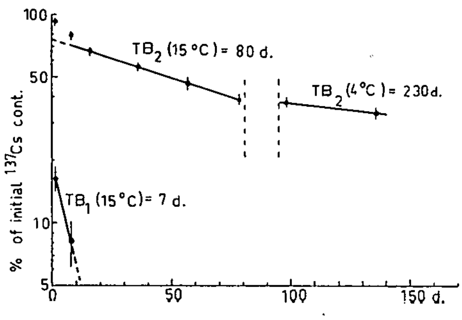

FIG. 2. ^{137}Cs retention in rainbow trout (15 fish) with biological variance (two σ) marked. At least two components are noticeable in the retention at 15°C: a "short" one having a half-time 7 ± 3 days (TB_1), and a "long" one, 80 ± 4 days (TB_2). At 4°C the value of TB_2 is 230 ± 10 days.

As can be seen from Table 1, perch has the longest half-time (TB_2), 200 ± 20 days at 15°C. There may be some increase in the value of TB_2 with the ageing of the fish, but the change is not clear. As the youngest age group (0.5 to 1 year) was labelled externally the results are not strictly comparable with the others.

In roach the half-time (50 days) in young fish is about half of that in old fish (100 days). The age dependence is clear also in rainbow trout as is the temperature dependence in rainbow trout and in the crusian carp. The table is incomplete in many respects due to technical difficulties. In laboratory experiments these include lack of space, presence of impurities in tap water, malfunction of thermostats and occasional infectious diseases. The field experiments have the advantage of more natural conditions, but the disadvantage that the water temperature cannot be kept constant. It was concluded from parallel determinations and parallel experiments that the accuracy of the data presented is better than 10%. Because the biological variance is rather large (see above) it is for most purposes not meaningful to have the average value determined with much higher accuracy; and in any case this would be very cumbersome.

In experiments made with oral labelling of perch and roach the percentage of the short component was 4 to 10%. In rainbow trout it was 25 ± 1% in three experiments, but 34% in one experiment. A large percentage is understandable in salmon which have rapid metabolism and short half-time (TB_2). The high percentage in the crucian carp is exceptional. There was no excretion during the first 24 hr, then about 50% of intake was suddenly excreted during the next 24 hr, and after that a very slow excretion rate (TB_2 55–120 days) was observed.

The results for ^{22}Na are presented in Table 2. The presence of a short component in the excretion curve for sodium is not always clear. From perch and roach a small amount (5 ± 3%) was consistently excreted very rapidly, and from rainbow trout 20% at 6°C but none was observed at the higher temperatures. As the long component was only 2.2 to 2.5 days it would have needed measurements at 1 hr intervals to notice the short one, but these were not made. No signs of a third component were noticed although most of the experiments were continued for several half-times (30 to 40 days).

Table 2. Biological Half-time of ^{22}Na in Five Species of Freshwater Fish

Fish	Age, yr.	No. of fish in expt.	Temp. °C	Biol. half-time of ^{22}Na, days
Perch	1–2	6	20 ± 0.2	7
		5	8 ± 3	15
Roach	1–2	5	20 ± 0.2	7
		5	8 ± 3	11
Rainbow trout	0.5–1	7	20 ± 0.2	2.2
		11	14 ± 1	2.5
		10	7 ± 1	7
Crusian carp	5	30	20 ± 0.2	10
		30	8 ± 3	25
Burbot	5	1	8 ± 3	30

Temperature dependence seems to be similar to ^{137}Cs-excretion: a 10° temperature decrease (from 15 to 5°C) reduces the excretion rate to about one-half.

CONCLUSIONS AND DISCUSSION

It is of interest to compare the above results with those obtained elsewhere, although the species are evidently different in all cases. Dean *et al.*(6) have studied the uptake and excretion of ^{137}Cs in different tissues of another species of rainbow trout, *Salmo gairdneri*. By injecting 10 μCi intravenously into yearling fish they found the "effective half-time" (TB_2) of ^{137}Cs in red muscle 5½ days, in white muscle 13 days. The curves published also suggest the existence of a short component of less than a day in most tissues (heart, gills, blood, liver, kidney). Temperature was not given, but if it was around 20°C and the whole body burden was determined by the white muscle, 13 days corresponds approximately to our value of 19 days at 14°C in *Salmo iridaeus*. Scott(7) reports 47 days for the brook trout (*Salvelinus fontialis*) and Ichikawa(8) 5 to 10 days for salmon (*Salmo salar*). Rudakov(9) has studied Crusian carp (*Cyprinus* sp.) and reports 10 to 15 days, but this value may represent the short component. Our values for TB_2 in the Crusian carp are 55 and 120 days at 20 and 8°C, respectively, but there may be a different species in question. Kevern *et al.*(10) report for the carp (*Cyprinus carpio*) 98 days at 20°C and 174 days at 12.5°C, i.e. about similar temperature dependence as found in this work. From the data of Williams and Pickering(11) we can estimate for very young bluegills (2 g each) the fast component to be about 3 to 4 days, the slow one 40 days. Nelson and Early(12) report the same value, 40 days, for blue gills (*Lepomis macrochirus*). Baptist and Price(13) studied retention of ^{137}Cs in skin, muscle, liver and gonad of the Atlantic croaker fish (*Micropogon undulatus*) finding that each tissue required multiple rate functions involving two or four exponents. Muscle had the longest retention time and it evidently governed the whole body retention. In most of the above studies the age of the fish and the water temperature are not given.

It is evident from the present results, and from those of the earlier workers, that the excretion rate of ^{137}Cs in fish varies greatly, by at least one order of magnitude. For instance, old perch has a two times longer half-time (200 days) than the old roach (100 days). ^{137}Cs body burdens in perch have been in most Finnish lakes 3 to 6 times higher than in roach.(4) Half of this difference is evidently due to different food activity as perch eats mainly small perch, but roach plankton and bottom animals,[14] half to different half-times. As shown in the above paper by us,[14] if one knows the ^{137}Cs body burden in a fish species at intervals of one to two half-times, and the percentage and value of the long component, one can calculate very accurately the daily intake of ^{137}Cs by the fish. Direct intake of ^{137}Cs through gills is so small that it can be neglected.[4] If, in addition, the activity of the food of the fish is known, one can calculate the food intake by the fish, a factor which is of great interest to fish investigators, and otherwise difficult to determine. Food intake by roach was in this way estimated in 6 lakes and found to vary from 0.8 to 2.3% of the weight of the fish per day. The intake was lowest in eutrophic lakes where a large number of small fish evidently limited the amount of food available. The annual growth of the fish was greater in the oligotrophic lakes where the food intake was greater, too.[14]

These examples show that some benefit may be obtained from the worldwide fallout to ecology and limnology.

ACKNOWLEDGEMENTS

Financial support for this investigation was obtained from the U.S. Department of Health, Education and Welfare (Public Health Service Research Grant No. RH-00307).

We are much indebted to the Kalamiesten keskusliitto organization for allowing us to use in these studies their fish hatchery facilities at Kytäjä.

It is a pleasure to acknowledge skilful technical assistance by Mr. Seppo Takatalo, Cand. Sci., and Mr. I. Vöry.

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Reprinted from

PROCEEDINGS OF THE FIRST INTERNATIONAL CONGRESS OF RADIATION PROTECTION

held at Rome, Italy, September 5-10, 1966

PERGAMON PRESS - OXFORD & NEW YORK - 1968

^{137}Cs IN THE PLANTS, PLANKTON AND FISH OF THE FINNISH LAKES AND FACTORS AFFECTING ITS ACCUMULATION

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Abstract—Bioaccumulation of ^{137}Cs in the fresh water organisms was studied during 1964 and 1965 by taking water, plankton, plant, bottom animal, and fish samples from water courses representing widely different limnological types: from eutrophic (rich in nutrients) to oligotrophic (nutrient deficient) lakes.

It was shown that the ^{137}Cs content of all organisms sharply depends on the potassium content of the water. In lakes where this value is less than 1 mg K/l. water, very high values of ^{137}Cs in fish were reached in 1965—max. 26 nCi/kg fresh weight in perch (*Perca fluviatilis* L.).

Quantitative estimations show that the four main factors determining the ^{137}Cs body burdens in the last link of the food-chain, the fish, are:

1. ^{137}Cs content of water—a minor factor as observed differences in the lakes studied have been only about 2- to 3-fold.
2. The limnological type of the lake—this is the main factor effecting 10- to 100-fold differences in the same fish species in different lakes.
3. The quality of food eaten by the fish—a minor factor effecting 2- to 3-fold differences.
4. The biological half-time of ^{137}Cs in fish—an important factor varying from 20 to 200 days at 15°C in different species and effecting up to 10-fold differences in various species in the same water course.

The bulk of the ^{137}Cs intake takes place through food chains. Direct gill absorption plays a minor role only.

INTRODUCTION

It was observed in 1961–62 that the ^{137}Cs content of fish in Finnish lakes was high (1 to 5 nCi/kg fresh wt.)(1) compared with values reported from northern Germany (10 to 100 pCi/kg fresh wt.).(2) This was astonishing insofar as the cumulative fallout in Finland is only from one-half to two-thirds of that in Germany. Great variations in the ^{137}Cs content of the same fish species in lakes of different limnological types were observed, also.(1) This led to a more systematic study, in 1963, of the factors governing the ^{137}Cs uptake in fish. Up to 100-fold differences in the ^{137}Cs content of fish in 12 lakes and 3 rivers of widely different limnological types was found.(3) For instance, in perch (*Perca fluviatilis* L.) the ^{137}Cs content varied from 0.2 to 20 nCi/kg fresh wt., in pike (*Esox lucius* L.) from 0.16 to 16 nCi/kg fresh wt., when the limnological type changed from eutrophic (rich in nutrients) to oligotrophic (nutrient deficient). Simultaneously, the electrolytic conductivity varied from 79 to 11 mho, resp.(3) In a later publication it was shown by us that it is the potassium ion which determines the ^{137}Cs level of the whole fresh water biota.(4) As different fish species in the same water have different ^{137}Cs content, other factors must function in addition. It is the purpose of this paper to discuss the relative importance of four main factors effecting the ^{137}Cs uptake in fish: the ^{137}Cs and potassium content of the water, the kind of food consumed by the fish, and the biological half-time of ^{137}Cs in the fish.

RESULTS

Samples of water, plankton, higher plants, bottom animals and fish have been collected since 1962 from a total of 23 lakes and 3 rivers representing widely different limnological types. There has been some variation in different years in the lakes studied, but those under study in 1964 and 1965 are presented in Table 1. The limnological type varies from fully eutrophic (No. 1) to dys-oligotrophic (No. 10a). A few of the limnological characteristics determined are presented in Table 1. Other factors determined were color, pH, and the frequency of plant and animal species which were used for characterization of the lake type. The methods and techniques used have been described earlier.[1, 3, 4]

1. *^{137}Cs content of the water* varied in the lakes studied (see Table 1) from 0.3 to 1.2 pCi/l. in 1964, when the highest values were observed in most of these lakes. A larger survey of Finnish surface waters was carried out by the Institute of Radiation Physics, which reports values between 0.2 and 2 pCi/l. in Finnish lakes in general.[5] Thus, variations in the amount of fallout were small compared with up to one-hundred-fold variations observed in the body burdens of fish.

2. *The limnological type of the lake.* This is the main factor affecting great differences in the ^{137}Cs content of the whole biota, as is evident from Tables 2 to 6.

In Table 2 there are presented the ^{137}Cs content of plankton samples from 7 lakes in 1964 and 8 in 1965. Analysis of 8 stable elements in these same samples (1964) as well as in the corresponding waters have been published earlier,[6] together with the frequency of species present. Composition of the samples collected in 1965 is presented in Table 3. Comparison between different years and lakes is made difficult by the fact that the composition of the samples—even from the same lake at different times—varies greatly. In addition, the fat content of some species (*Diaptomus*, *Cyclops*, *Daphnia* and *Bosmina*) varies at different times and one specie (*Holopedium gibberum*) may contain up to 90% of slime, which causes great differences in the percentage of dry matter. If the sample contains diatoms, these increase the ash content. However, the ^{137}Cs content per g of dry wt., and especially per g of potassium, changes rather regularly being lowest in the sample taken from the eutrophic lake 1 and highest in one of the oligotrophic lakes 4 to 9. The difference between the extreme values is 10- to 500-fold.

Table 1. Limnological Analyses of the Finnish lakes studied during 1964 *and* 1965.

No.	Lake	Date	Cond. mho 18°C	KMnO cons. mg/l.	Na mg/l.	K mg/l.	Ca mg/l.	^{137}Cs pCi/l.	Limnological lake type
1	Niemenjärvi	9.9.65	85	75	5.2	3.5	8.8		eutrophic
		16.7.64						0.8	
2	Kytäjärvi	8.9.65	72	45	3.0	1.8	7.4		dys-eutrophic
		14.7.64						0.3	
3a	Pyhäjärvi	19.9.65	71	32	3.5	2.4	8.0		eutrophic
3b	Ilmoilanselkä	20.7.65	58	35	2.8	1.7	6.0		eutrophic
3c	Päijänne	2.7.64	47	43	3.8	1.0	4.8	1.2	±eutrophic
3d	Näsijärvi	25.6.64	75	120	5.8	1.0	6.0	1.0	dys-oligotrophic
4	Suolijärvi	11.8.65	44	65	2.2	0.9	4.4		dys-oligotrophic
		14.7.64						0.8	
8	Melkutin	22.6.65	43	6	2.1	1.0	5.8		oligotrophic
		6.9.64						0.5	
9a	Vuohijärvi	3.6.65	31	32	1.8	0.8	3.4		oligotrophic
		14.8.64						1.2	
9b	Keritty	30.7.65	26		1.7	0.6	2.5		dys-oligotrophic
10	Mutkajärvi	23.7.64	16	100	1.3	0.2	1.0		dys-oligotrophic
10a	Akulampi	24.8.65	15		1.3	0.4	1.0		dys-oligotrophic

Table 2. Radiochemical Analyses of Plankton Samples 1964–65

Lake No.	Date	Dry wt. % of fresh wt.	Ash wt. % of dry wt.	^{137}Cs pCi/l.	^{137}Cs pCi/g dry wt.	K mg/g dry wt.	^{137}Cs pCi/mg K	Phyto-plankton, % of plankton
				1964				
1	17.7	2.90	15.6	45	1.51	17.3	0.09	
2	13.7	3.36	15.8	105	3.12	18.8	0.17	
3a	18.9	4.38	13.3	180	4.08	15.2	0.27	5
3d	25.6	2.15	24.8	250	13.2	10.7	1.23	25
4	13.7	7.80	19.5	120	16.0	11.4	1.40	25
8	6.9	5.62	5.0	730	11.9	9.7	1.22	
9a	11.8	3.75	13.5	600	15.9	12.7	1.25	
				1965				
1	9.9	3.17		50	1.48	55.1	0.003	
2	8.9	2.49		110	4.17	8.6	0.48	35
3a	10.9	4.11		90	1.97	20.9	0.09	5
3b	20.7	4.43		260	5.29	28.5	0.19	
3d	16.9	4.35		250	9.25	21.5	0.43	
4	28.7	2.84		440	9.05	23.9	0.38	
8	23.6	0.42		120	27.22	14.5	1.88	
9b	30.7	5.48		360	16.86	19.1	0.88	

This same tendency is usually visible from the ^{137}Cs values of the higher plants, especially species rich in minerals like the Horsetail (*Equisetum fluviatile*). Values for two higher plants, *Equisetum fluviatile* and the Yellow Water Lily (*Nuphar luteum*) from the years 1964 and 1965 are presented in Table 4. Again the ^{137}Cs content is lowest in the eutrophic lakes Nos. 1 to 3, highest in the oligotrophic lakes Nos. 9 and 10. The values of higher plants do not always change regularly, however. One cause of the irregularities may be the algae living on the surface of the plants.

Relatively few samples of bottom animals have been obtained. Even in the eutrophic lakes it is a difficult task to obtain large enough samples of any single species for gamma-spectrometric analysis, and in the oligotrophic lakes it is even more difficult. Results on three samples from the years 1963 and 1964 are presented in Table 5. As can be seen, the value for *Chaoborus* sp. in lake No. 1 in 1964, 1.44 nCi/kg dry wt., is practically the same as that of the simultaneous plankton sample from this lake (1.51 nCi/kg dry wt.). The ^{137}Cs content of the *Trichoptera*-larvae, on fresh weight basis, is about 3.5 times greater, but the potassium content in this lake is only one-third of that in Lake No. 1, as can be seen from Table 1.

Most clear-cut is the inverse relationship of the ^{137}Cs content of fish and the potassium content of the lake water. In an earlier paper[4] this relationship was shown for several fish species. It is also evident from Table 6 and Fig. 1 of this paper. As can be seen in Fig. 1 down to a potassium content of 1 mg/l. the ^{137}Cs content of pike remains low (< 3 nCi/kg), but with the potassium content 0.6 mg/l. it reaches the very high value 21.3 nCi/kg fresh wt. The same regular relationship is visible in other species (Table 6). The larger sized perch have the highest ^{137}Cs content, which in one lake (No. 9b) was 26.2 nCi/kg fresh wt. This is the highest ^{137}Cs content of fish obtained anywhere in natural waters, as far as we know.

3. *^{137}Cs content of the food.* Small perch contain only about one-half of the level in the larger perch, the difference evidently being due to

Table 3. Description of Plankton Samples collected from lakes of Table 2 in 1965.

Lake No.	Lake name	Date	Sample volume ml	Dry weight g	Phytoplankton	Group	%	Zooplankton	Group	%
1	Niemenjärvi	9.9.65						*Eudiaptomus cracilis*	Copepoda	90
								Ceriodaphnia palchella	Cladocera	
								Daphnia cucullata	Cladocera	5
								Cyclops sp.	Copepoda	5
2	Kytäjärvi	8.9.65	96	2490	*Melosira varians*	Diatomae	10	*Bosmina coregonii*	Cladocera	10
					Asterionella formosa	Diatomae	5	*Cyclops* sp.	Copepoda	45
					Melosira islandica	Diatomae	20	*Daphnia cucullata*	Cladocera	10
3a	Pyhäjärvi	10.9.65	190	9211	*Anabaena circinalis*	Cyano-phyta		*Chydorus sphaericus*	Cladocera	30
					Microcystis aeruginosa	,,	5	*Eudiaptomus cracilis*	Copepoda	10
								Bosmina coregonii	Cladocera	25
								Cyclops sp.	Copepoda	5
								Daphnia cucullata	Cladocera	25
3b	Ilmoilanselkä	20.7.65	464	22,170				*Bosmina coregonii*	Cladocera	10
								Daphnia cucullata	Cladocera	75
								Mesocyclops hyalinus	Copepoda	15
3d	Näsijärvi	16.9.65	288					*Bosmina obtusirostris*	Cladocera	40
								Daphnia longispina	Cladocera	15
								Eudiaptomus craciloides	Copepoda	10
								Mesocyclops leuckartii	Copepoda	35
4	Suolijärvi	28.7.65	230	11,351				*Bosmina coregonii*	Cladocera	15
								Daphnia cucullata	Cladocera	70
								Mesocyclops hyalinus	Copepoda	15
8	Iso Melkutin	23.6.65	500	2012				*Eudiaptomus cracilis*	Copepoda	40
			490	2202				*Bosmina obtusirostris*	Cladocera	10
								Heterocope borealis	Copepoda	25
								Holopedium gibberum	Cladocera	25
9b	Keritty	29.7.65	500	10,948				*Daphnia cucullata*	Cladocera	40
								Chydorus sphaericus	Cladocera	10
								Diaphtomus brachyurum	Copepoda	40
								Cyclops sp.	Copepoda	10

Table 4. ^{137}*Cs Content of Two Water Plants in* 1964 *and* 1965

No.	Lake	1964				1965			
		Horsetail (*Equisetum fluviatile*) ^{137}Cs		Yellow Water Lily (*Nuphar luteum*) ^{137}Cs		Horsetail (*Equisetum fluviatile*) ^{137}Cs		Yellow Water Lily (*Nuphar luteum*) ^{137}Cs	
		nCi/kg d.w.	nCi/g K	nCi/kg d.w.	nCi/g K	nCi/kg d.w.	nCi/g K	nCi/kg d.w.	nCi/g K
1	Niemenjärvi			0.68	0.03	1.9	0.15	0.67	0.04
2	Kytäjärvi	2.3	0.10			1.1	0.05	0.82	0.03
3a	Pyhäjärvi	3.7	0.16			2.2	0.10		
3b	Ilmoilanselkä					1.9	0.06		
3d	Näsijärvi	8.9	0.43	6.62	0.28	6.7	0.40	7.10	0.26
4	Suolijärvi	4.9	0.17					5.66	0.28
9a	Vuohijärvi	44.8	2.03	12.20	0.66				
9b	Keritty					16.9	0.84	23.3	1.28
10a	Akulampi					92.5	3.40		

Table 5. *^{137}Cs Content in Two Species of Bottom Animals,* 1963 *and* 1964

Lake No.	Lake name	Date	Specie	^{137}Cs, pCi per kg fresh wt.	^{137}Cs, pCi per kg dry wt.	^{137}Cs, pCi per g K	K, g per kg dry wt.
1	Niemenjärvi	11.6.63	*Chaoborus*	70	800	66	1.22
		16.7.64	*Chaoborus*	90	1440	—	—
3c	Päijänne	4.8.64	*Trichoptera*	330	—	122	(2.7 per kg fresh wt.)

variations in the diet. The small perch consumes mainly plankton and bottom animals, the larger ones small fish. However, roach, bream and whitefish also eat plankton, bottom animals and water plants like small perch, but they have lower ^{137}Cs content than the latter. To understand this, however, it is necessary to study the fourth factor affecting the body burdens in fish.

4. *The biological half-time of ^{137}Cs in different fish species.* As shown in another paper in this meeting,[7] the biological half-times of fish (the "slow" component) varies from 20 to 200 days at 15°C. Perch has the longest half-time of those hitherto determined—200 days at 15°C. This is evidently one of the main reasons for its high body burden. At 5°C the excretion of ^{137}Cs is slowed down to about one-half of the value at 15°C. In perch, the half-time of ^{137}Cs does *not* change noticeably in different ages but in roach (*Leuciscus rutilus*) the old fish (9 to 12 years) have about a two times longer half-time (100 days at 15°C) than the young ones (2–3 years old, 57 days at 15°C). In rainbow trout (*Salmo iridaeus*) the change is even greater: 0.5 years: 20 days; 1 to 2 years: 55 days; 2 to 3 years: 80 days, all at 15°C. Pike (*Esox lucius*) also has a relatively long half-time of ^{137}Cs (unpublished) which corresponds well to its high body burden. As the annual mean temperature in the Finnish lakes is low—usually around 4 to 6°C—the average half-times the year round in

Table 6. *^{137}Cs Content of Fish in some Finnish Lakes during summer* 1965

No.	Lake	Perch (*Perca fluviatilis*) smaller <20 cm	Perch (*Perca fluviatilis*) larger >20 cm	Pike (*Esox lucius*)	Burbot (*Lota vulgaris*)	Roach (*Leuciscus rutilus*)	Bream (*Abramis brama*)	Whitefish (*Coregonus* sp.)
		nCi per kg fresh weight						
1	Niemenjärvi		0.24	0.25		0.18	0.06	
2	Kytäjärvi	0.52	1.49	0.99	0.63	0.30	0.21	
3a	Pyhäjärvi	0.79		0.60		0.37		
3b	Ilmoilanselkä		2.16	1.38		0.71		
3c	Päijänne	1.10	2.17		3.02	1.18		
3d	Näsijärvi	2.60		2.66	2.87	1.20	0.80	
4	Suolijärvi	3.35	7.92	4.91	2.48	1.14		
8	Melkutin	5.97				2.73		1.75
9a	Vuohijärvi	9.39	13.18	7.07	6.26	4.23		2.78
9b	Keritty		26.25	21.27		6.29		3.55

these predatory fish species must be of the order of one year. This explains also why the ^{137}Cs values in many lakes were still increasing in 1965. This seems to be true especially in the oligotrophic lakes (lake No. 9a; perch 1964 7.9, 1965 13.2 nCi; pike 1964 6.5, 1965 7.1 nCi; burbot 1964 4.3, 1965 6.3 nCi; roach 1964 3.3, 1965 6.3 nCi per kg of fresh wt.).[4] In eutrophic and some oligotrophic lakes a slight decrease has taken place.

CONCLUSIONS AND DISCUSSION

Our results presented above suggest that ^{137}Cs remains in circulation within the biokenosis in the oligotrophic lakes a longer time than in the eutrophic lakes. The reason for this may be a greater content of clay particles, a faster sedimentation, or a slighter depth and a smaller volume of the eutrophic lakes in general. It is evident that the ^{137}Cs contamination of the biota is accentuated in two ways in the oligotrophic waters: the enrichment of ^{137}Cs is increased because of the low potassium level, and it remains high longer. The long half-times in perch and pike, about one year in natural conditions, during the longer pollution times effect continuous increase of the body burdens of fish.

The biological half-times of the lower animals are generally short, a few days or even hours. For instance, in mayfly nymph (*Ephemera varia*; *Ephemerida*) the half-time of ^{137}Cs is 8.3 days, in the midge larvae (*Chionomus commutatus; Diptera*) 3.5 days.[8] Thus, their activity closely follows the ^{137}Cs level of the water.

Except through food, fish take up ^{137}Cs directly from water by the osmotic mechanisms in the gills. However, this intake is relatively unimportant compared with the intake through food. Preliminary experiments with young rainbow trout in an oligotrophic water show that within one biological half-time (*ca.* 25 days) the fish obtain a specific activity which is about 10 times higher than that of the water. The present ^{137}Cs levels in the Finnish surface waters, about 1 pCi/l., would thus correspond in equilibrium state to a body burden of about 20 pCi/kg which is negligible compared with the values observed in oligotrophic lakes. We can come to about the same conclusion by estimating from the data published by Friend *et al.*[9] (their Figs. 3–6).

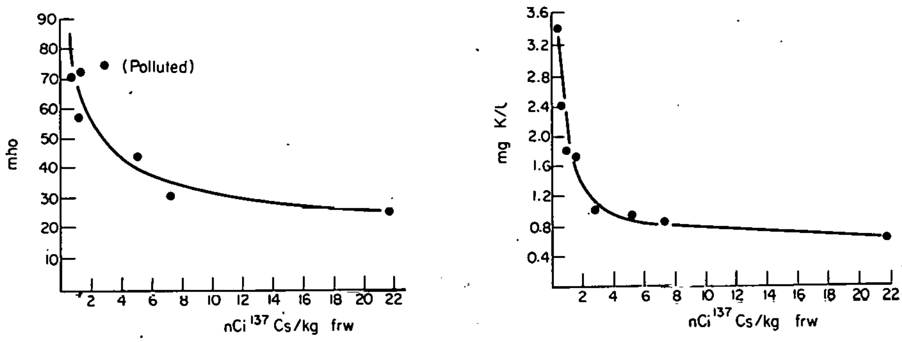

FIG. 1. ^{137}Cs content of pike in different types of lakes in summer 1965 as a function of conductivity (left) and potassium content of the water (right).

In reality, a ^{137}Cs content of about 1 pCi/l. effects in oligotrophic lakes in the fish of prey body burdens of 5 to 20 nCi/kg, in other fish about 1 to 5 nCi/kg fresh wt., in eutrophic lakes correspondingly 0.2 to 2 and 0.1 to 1 nCi/kg fresh wt., respectively. The bulk of the body content is thus obtained through food.

The correctness of the above quantitative interpretations was checked in an earlier study[4] by calculation of the intake in diet of ^{137}Cs and of dry matter by perch and roach. The amount of food intake calculated in this way was found to be reasonable when compared with estimations by other means. In different lakes it was in direct relationship with the growth rate of roach. It is thus evident that the calculations are essentially correct.

Relatively little ^{137}Cs analyses of fresh-water fish have been published elsewhere. In the U.S.A. the fresh water studies have been mainly concentrated to "on-site" areas like the Columbia River and White Oak Creek, where the discharged activity is mixed with fallout-activity and nuclide concentration is rapidly reduced downstream. Although locally important, such studies warrant little generalization. Some results on fish from natural fresh waters have been published from Alaska and the Great Lakes region, however. Watson and Rickard[10] report in whitefish and grayling from two Alaskan lakes during the summer 1962 1.9 and 0.6 to 2 nCi/kg dry wt., respectively, values which are small compared to those from Lapland at the same time—whitefish 7, grayling 5 to 9 nCi/kg dry wt.[1] Gustafson[11,12] reports for fresh water fish purchased during 1965 in food markets in the Chicago area, the following values: northern pike 1.1 to 4.1, lake perch 0.3 to 1.1, and whitefish 0.18 to 2.8 nCi/kg fresh wt., values comparable with our values for corresponding species in eutrophic or slightly oligotrophic lakes.

Lidén,[13] in an oligotrophic lake (K 1 mg/l.) in southern *Sweden* during 1962 and 1963 found in pike 2 to 4 nCi/kg fresh wt., values quite similar to ours.[1] Hannerz[14] reports from the years 1964 and 1965 in the eutrophic lake Mälar, near Stockholm, for pike and pike-perch 0.9, for perch and burbot 0.8, roach 0.4 and bream 0.25 nCi ^{137}Cs/kg fresh wt., values 2 to 4 times higher than those in the same species in the Baltic, and supposes the difference to be due to different potassium concentrations in the water.

Values for *German* fresh water fish and waters are regularly published in the quarterly reports of the Ministry of Science.[15] Pike contained 5.7 to 9.9 nCi, carp (*Cyprinus carpio*) 5.4 nCi and tench (*Tinca vulgaris*) 3.2–11.0 nCi/kg fresh wt. in the lake Kolksee (Ostholstein) having 1.8 mg K and 6.6 pCi ^{137}Cs/l. (ref. 15, I/65, pp. 107–108). Feldt (ref. 15, III/65, pp. 169–183) gives the following relationship for three fresh waters in Germany:

	Kolksee	Gr. Plöner See	Elbe
K content in water, ratios	1	5	10
^{137}Cs/g K in fish, ratios	300	30	1

From *Italy*, values for perch in four lakes are reported from the year 1963.[16] While our values varied from 0.2 to 20.4 nCi/kg,[3] those from the four Italian lakes studied, the Lake Maggiore, Varese, Comabbio and Monate, were in June 1.1, 1.2, 2.8 and 7.4, and in September 1.9, 3.3, 5.2 and 6.3 nCi/kg, respectively. These values are about in the middle of our range, our lakes evidently representing a much wider range of limnological conditions. The unpolluted Alp lakes are usually oligotrophic.

Hannerz[14] reports for plankton (mainly *Limnocalanus* and *Diaptomus*) during summer 1964 in Lake Mälar, Sweden, *ca.* 90 to 130 pCi/l. which corresponds to our plankton value in lake No. 2 (105 pCi/l.); to summer 1965 his values had decreased to about one-half of those in the previous year. For plankton in the Kolksee, Germany, 1.6 nCi/kg dry wt. is reported for April 1964 (ref. 15, I/65, p. 108), which corresponds to our plankton value in the most eutrophic lake No. 1 (1.5 nCi/kg). For horsetail in the same lake 4.0 nCi in stem below water, 9.2 nCi in stem above water per kg dry wt. is reported (ref. 15, II/65, p. 103). This corresponds to our lakes 3 to 4 but is only one-tenth of the horsetail activity in our lake No. 10 (92.5 nCi/kg dry wt. in stem above water).

Several authors who have studied the uptake of ^{137}Cs in lower organisms have observed the negative effect of potassium-ions in the water. Rice[17] observed it while studying algae, Williams[18, 19] while studying *Euglena* and *Chlorella*, and Bryan and Ward[20] while studying ^{137}Cs uptake in crustaceans.

SUMMARY

It can be generalized that uptake of ^{137}Cs in the whole biota of a fresh water lake is sharply accentuated especially if the potassium content of the lake water is below 1 mg/l. The four main factors affecting the ^{137}Cs body burdens in fish are:

1. ^{137}Cs content of water—a minor factor, as observed differences in the lakes studied have been only 2- to 3-fold.
2. Potassium content of the water—a major factor effecting 10- to 100-fold differences and very high ^{137}Cs levels in the whole biota in the most oligotrophic lakes.
3. The quality of food eaten by the fish—a minor factor effecting 2- to 3-fold differences.
4. The biological half-time of ^{137}Cs in fish—a major factor varying from 20 to 200 days at 15°C and effecting up to 10-fold differences in various species in the same water course.

ACKNOWLEDGEMENTS

Financial support for this investigation by the Finnish Atomic Energy Commission and the U.S. Department of Health, Education and Welfare (Public Health Service Research Grant No. RH-00307) is gratefully acknowledged.

It is a pleasure to acknowledge skillful technical assistance by Mr. Seppo Takatalo, Cand. Sci., and Mr. I. Vöry.

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Annals of Clinical Research 3: 236—240, 1971

THE BIOLOGICAL HALF-LIFE OF ^{137}Cs AND ^{24}Na IN MAN

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ABSTRACT

Excretion of ^{137}Cs and ^{24}Na and the factors affecting it were studied in 10 healthy men. The biological half-life found for ^{137}Cs was 84 days (52—104 days) and that for ^{24}Na 9.3 days (5.1—13.1 days). The amount of exchangeable sodium was, on the average, 1.14 g/kg and caesium 0.025 mg/kg. The biological half-life of ^{137}Cs was found to be significantly correlated with the amount of ^{137}Cs excreted in urine during the first 24 hours after a single oral dose ($r = 0.83$, $p < 0.001$) and with the amount of sodium excreted in urine ($r = -0.81$, $p < 0.01$). The biological half-life of ^{24}Na was found to be correlated with the amount of stable sodium excreted in urine ($r = -0.71$, $p < 0.01$).

KEY WORDS: BIOLOGICAL HALF-LIFE; Cs-137; Na-24; WHOLE-BODY COUNTING

INTRODUCTION

When investigating the metabolism of different alkali metals in man (13, 14) the shortest biological half-life ($BT_{1/2}$) was for sodium and the longest for caesium.

Special interest has been taken in caesium, because its radioactive isotope ^{137}Cs forms one of the two main components in the long-lived global fallout, the other being ^{90}Sr. Of the other alkali metals potassium bears the strongest resemblance metabolically to caesium. These two appear mainly in the intracellular volume, while sodium appears mainly in the extracellular volume.

When following the elimination of ^{137}Cs from after, for example, a single oral dose, it can be seen that about 10 % of the administered ^{137}Cs is eliminated rapidly with a $BT_{1/2}$ value of about one day. After this the elimination rate decreases and the biological half-life reaches a value of about 100 days. The biological half-life is usually considered to be the $BT_{1/2}$-value of this slow component.

The biological half-life values of ^{137}Cs vary greatly (100 ± 50 days) (12). It is clearly shorter in children than in adults, longer in males than in females increasing with age, and showing a decrease during pregnancy (1, 2, 10, 17). The shorter half-life values measured in Scandinavia have been supposed to be due to dietary differences or to changes in metabolic rate (6, 15).

The purpose of this investigation was to find a factor to account for the variation in the biological half-life of ^{137}Cs noticed between different individuals. It is possible that these differences may be caused by the variation in the individual intracellular and extracellular states (9). Special attention was therefore paid to exchangeable sodium and the biological half-life of sodium which describe the extracellular state, while the potassium values of the whole body give information on the intracellular state.

TABLE 1

Age, height and weight of the subjects.

Subject	Age years	Height cm	Weight kg
JA	29	160	54
RE	35	175	81
JH	24	172	77
TH	27	187	77
UH	28	179	77
EH	38	188	69
RL	28	180	72
ST	30	170	64
RT	27	172	58
IV	28	161	73
Average	29	174	70

MATERIAL AND METHODS

A group of 10 men was investigated. The mean age was 29 years, mean height 174 cm and mean weight 70 kg (Table 1). The whole-body counting measurements were done using a 8" x 4" NaI(Tl)-crystal and a 512-channel pulse height analyzer. Chair-geometry was used, and an »iron room» having 14 cm thick walls as background shields.

^{24}Na and stable Na. Each subject was given orally approximately 10 μCi ^{24}Na ($T_{1/2} = 15.05$ h).

The biological half-life of ^{24}Na was determined by repeated whole-body counting that was continued for as long as any ^{24}Na-activity could be detected, that is for approximately one week.

The urine voided during the first 24 hours was collected and ^{24}Na and stable Na determined. From a separate urine sample taken 24 hours after the administration of the radioactive sodium, the ^{24}Na was determined radiometrically and the stable sodium with an atomic absorption spectrophotometer. The exchangeable sodium of the subjects could then be calculated.

^{137}Cs and stable Cs. About one month after the ^{24}Na experiment, the same subjects were given orally approximately 0.4 μCi ^{137}Cs ($T_{1/2} = 30.0$ years).

In order to determine the biological half-life of ^{137}Cs the ^{137}Cs-content of the body was followed by repeatedly whole-body counting for four months.

The ^{137}Cs excreted during the first day was determined. The stable caesium in the 24 hour urine sample taken earlier was determined by activation analysis (5).

Stable K. The potassium content of the subjects was determined by whole body counting, recording the 1.46 MeV radiation of ^{40}K. The K-content of the 24 hour urine sample was determined by atomic absorption spectrophotometry.

RESULTS AND DISCUSSION

The results are presented in Table 2 and 3.

The biological half-life on ^{24}Na in the subjects ranged from 5.1 to 13.1 days, the average being 9.3 days. This is about 15 % shorter than the half-life in 3 men (11.0 days) in an experiment by Richmond using ^{22}Na. During the first day an average of 6.6 % of the ^{24}Na was excreted in the urine which agrees with the value reported by Richmond (6 %) (13).

The amount of exchangeable sodium was on the average 1.14 g/kg. This is 14 % higher than the average value (1.00 g/kg) for men of the same age and weight found by Moore et al. (8).

TABLE 2

Biological half-life of ^{137}Cs and ^{24}Na, exchangeable sodium, total body potassium and the ratio of exchangeable sodium to total body potassium.

Subject	$BT_{1/2}$, (days)		Exchang. Na		Total body K		Exchang. Na/ tot.b. K
	^{137}Cs	^{24}Na	g	g/kg	g	g/kg	
JA	52	5.1	44	0.82	92	1.70	0.478
RE	82	6.7	104	1.28	168	2.07	0.619
JH	99	13.1	111	1.44	132	1.71	0.841
TH	85	8.8	119	1.55	174	2.26	0.684
UH	101	8.3	73	0.95	131	1.70	0.557
EH	100	9.8	72	1.04	135	1.96	0.533
RL	104	10.6	83	1.15	156	2.17	0.532
ST	75	10.8	72	1.12	123	1.92	0.585
RT	59	8.6	73	1.26	136	2.34	0.538
IV	86	11.5	58	0.79	108	1.48	0.557
Average	84	9.3	81	1.14	136	1.93	0.590

TABLE 3

The amount of ^{137}Cs and ^{24}Na excreted in urine during the first 24 hours (after the administration of the dose), the amount of stable caesium, potassium and sodium excreted in urine and the daily intake of sodium calculated per body weight (kg) and day.

Subject	Excretion in urine in 24 hours, of % intake ^{24}Na	^{137}Cs	Stable Cs in urine µg/kg/day	Stable K in urine mg/kg/day	Stable Na in urine mg/kg/day
JA	11.6	7.9	0.18	46	85
RE	8.2	5.1	0.22	34	75
JH	6.1	2.1	0.20	34	46
TH	5.5	6.4	0.12	49	60
UH	3.5	2.8	0.10	38	51
EH	6.8	5.2	0.12	34	71
RL	5.2	5.0	0.14	35	50
ST	6.8	7.8	0.17	33	70
RT	6.2	8.3	0.19	57	86
IV	6.5	5.4	0.37	42	49
Average	6.6	5.6	0.18	40	64

The amount of stable sodium excreted in the 24 hour urine samples was on the average 4.5 g/day which corresponds to daily intake 5.3 g (3).

The biological half-life of ^{137}Cs ranged from 52 to 104 days, the average being 84 days. In earlier studies the values for adults have been generally 100 ± 50 days. The result obtained agrees well with the result of 80 days for five men (mean age 29 years) by Fujita (4) et al., and with the values obtained by Boni (2), 67 days for subjects 15—30 years and 93 days 30—50 years old.

The amount of stable caesium excreted in 24 hour urine ranged from 7.5 to 26.4 µg, the mean being 12.6 µg. Since the amount of caesium excreted in urine is 87 % of the total (4), the amount of exchangeable caesium in the body can be calculated from the equation.

$$Q = \frac{BT_{1/2}}{0.693} \cdot \frac{U}{f_u}$$

where Q = body burden, $BT_{1/2}$ the biological half-life of caesium, U = urinary excretion per day, f_u = Cs in urine/Cs in total excreta (urine plus faeces).

The average amount of exchangeable caesium is then 1.76 mg which corresponds to the value of 25 µg Cs/kg. This result is 25 % higher than the value 20

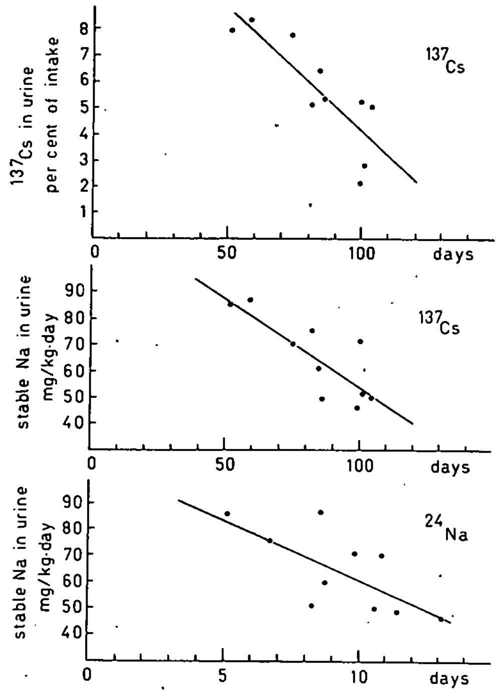

Fig. 1. Significant correlations observed in excretion of ^{137}Cs, ^{24}Na and stable Na.

(Top) The amount of ^{137}Cs excreted in urine during the first 24 hours after an orally given single dose/$BT_{1/2}$ of ^{137}Cs; $r = -0.83$, $p < 0.001$. (Middle) The amount of stable sodium excreted in 24 hour urine/$BT_{1/2}$ of ^{137}Cs; $r = -0.81$, $p < 0.01$. (Bottom) The amount of stable sodium excreted in 24 hour urine/$BT_{1/2}$ of ^{24}Na; $r = -0.71$, $p < 0.01$.

μg/kg for total caesium obtained by Yamagata (15) and about 200 times higher than the value recommended by the International Commission on Radiological Protection (11).

The amount of caesium eliminated in the urine during the first 24 hours was from 2.1 % to 8.3 % (average 5.6 %) of the administered dose. The fast component in the excretion of ^{137}Cs after a single oral dose probably corresponds to this value.

The potassium concentration of the body varied between 1.48 and 2.34 g/kg (body weight) and the average was 1.93 g/kg.

The amount of potassium excreted in 24 hour urine was 2.96 g, which corresponds to a daily intake of about 4 g (4). The results obtained match those found in the literature (9, 16).

The biological half-life of ^{137}Cs is significantly correlated to the amount of ^{137}Cs excreted in urine during the first 24 hours and the amount of sodium excreted in urine. The biological half-time of ^{24}Na is also correlated to the amount of stable sodium excreted in urine (Fig. 1).

No significant statistical correlation could be found between the biological half-life of ^{137}Cs and the ratio of exchangeable sodium to whole-body potassium ($r = 0.35$). It would seem probable therefore that the ratio of extracellular state to intracellular state has no clear effect on the excretion rate of ^{137}Cs.

On the contrary, the excretion rate of ^{137}Cs seems to be strongly dependent on the fast component in the excretion mechanism. Similarly, it is dependent on the amount of sodium excreted by kidneys. In previous long-term experiments in man adding potassium to the diet had no effect on the excretion rate of ^{137}Cs (7). The effect of sodium has not been investigated.

This study would indicate that the variations in the biological half-life of ^{137}Cs between individuals, and different population groups, are partly caused by the differences in the sodium content of the diet.

ACKNOWLEDGEMENT

We express our thanks to prof. J. K. Miettinen, Head of the Department of Radiochemistry, University of Helsinki and to prof. P. Jauho, Head of the Reactor Laboratory, Helsinki University of Technology, for the possibility to use excellent equipment. We also wish to express our thanks to the volunteers, who made this investigation possible.

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Received for publication: May 18, 1971

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