SUPPLEMENTARY FILE

This Supplementary File presents the work performed by various Member States' participants within the Coordinated Research Project (CRP): "Transfer of Radionuclides from Air, Soil, and Freshwater to the Food Chain of Man in Tropical and Sub-tropical Environments" (1993–1997). A full list of CRP participants is available in Table I-1 of Annex I of this Supplementary File.

The term transfer factor (TF) was more frequently used in the 1990s, when the CRP report upon which this Supplementary File is based was written, and it is used throughout Annexes II–XVI of this publication. Concentration Ratio (*CR*) parameter is now often used instead of TF to quantify environmental transfer, as described in Chapter 2 of the main TECDOC publication to which this current text is a Supplementary File.

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ANNEX I.

ENSURING THE QUALITY AND COMPARABILITY OF RADIOECOLOGICAL DATA

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I-1. QUALITY ASSURANCE

One of the problems with radioecological data is the wide range of observed values, due to the large diversity of ecological and agricultural conditions. Although in some cases a strict standardization of the experimental conditions reduces the range and biological variability of the data, assessments of the impact of radioactive discharges to the environment must take account of such diversity. A standardization of experimental conditions would be inappropriate for experiments designed to determine radioecological parameters intended to be used in such assessments. Instead, measures need to be taken to ensure that experiments carried out to determine radioecological parameters for this type of assessments reflect the local natural or agricultural conditions and practices.

One means for quality assurance within this Coordinated Research Programme (CRP) was by peer review of data provided by the participants at each of the coordination meetings. This provided an opportunity for the experts present to question the data in some detail before acceptance into the database. The transfer parameter data values from soil to plant determined by the different CRP participants are presented in Annexes IV–VII, IX–X, XII–XIV, XV–XVI and partially included in the MODARIA II tropical database (see Chapter 3 and Appendix II of the main TECDOC to which this current publication is a Supplementary File).

A further effort to ensure quality assurance was provided by the CRP participants taking part in interlaboratory analytical exercises and intercomparisons using IAEA reference materials. These are described in Section I-2 below.

Another aspect to ensure compatibility of results between CRP participants was the use of two experimental protocols that were developed for this purpose in the CRP and based on agreed IUR protocols: soil to plant (see Annex II below) and freshwater to fish (see Annex III below). The protocols emphasized the need for representative experiments that provided detailed documentation of the environmental conditions under which the studies were conducted. The use of these protocols would help to understand the causes of the range of observed data and might improve the extrapolation of the results to situations that were not investigated.

I-2. INTERCOMPARISON EXERCISE WITHIN THE IAEA COORDINATED RESEARCH PROJECT

A critical part of any radioecology programme is the quality of the analytical data being reported. It was recommended that intercomparison exercises with metrological institutes and/or organizations such as the IAEA, the US National Institute of Standards and Technology (NIST), the Environmental Measurements Laboratory of the US Department of Energy (EML) and the US Environmental Protection Agency (EPA), interlaboratory comparisons (gamma spectroscopy and radiochemistry) and analysis of split samples with other laboratories (gamma spectroscopy and radiochemistry) be carried out.

An example of an intercomparison exercise conducted as part of the CRP “Transfer of Radionuclides from Air, Soil, and Freshwater to the Food Chain of Man in Tropical and Subtropical Environments” is presented below. A list, in alphabetical order, of the teams who

participated in this CRP is given in Table I-1 below. The name of the group leader or leaders of the respective country and the respective organization of the team are summarized. Thereafter, each team is identified by the name of the leader or leaders as indicated in Table I-1. Additional data included in the CRP were provided by R. Avila Moreno, from the Swedish Radiation Protection Institute, Sweden, M.J. Frissel, from the Netherlands, J.M Osores from the Instituto Peruano de Energia Nuclear, Peru and S.I. Yamasaki, from the National Institute of Agro-Environmental Sciences, Japan.

A set of IAEA reference samples was provided by the IAEA to each of the CRP participants. Each group was requested to analyze the samples for ^{137}Cs, ^{134}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{60}Co, zinc and iodine or, at least, those radionuclide/element from this list that were used in their experiments. The original set of reference samples sent by the IAEA to each participant was:

(1) IAEA 375 (soil) (Reference date: 31 December 1991) and IAEA 6;
(2) IAEA 156 (clover) (Reference date: 1 August 1986);
(3) IAEA SL-3 (sediment) (Reference date: 11 January 1996); and
(4) IAEA-V8 (rye flour) (Stable elements only).

The first three samples were used for radionuclide analysis, while the last one, IAEA-V8, was intended for analysis of stable calcium and potassium. The original soil sample IAEA 375 sent to the Republic of Korea was misplaced, therefore a second soil sample, IAEA Soil 6, was sent to this group for analysis. The group from Taiwan, China has also chosen to analyze IAEA Soil 6.

Reporting of data – It was recommended that a logbook be used to describe and record all procedures as this would be valuable in comparing data. Data sheets were used within the CRP to guarantee that participants reported data in the same units and sequence. Use of this list facilitated statistical or other methods of data analysis. The values included in the database were collected via these data sheets.

The results of the intercomparison exercise obtained by all the participants for the five reference samples provided are given in Tables I-2–I-6. All activity concentrations on a dry mass (DM) basis were corrected to the appropriate reference date of the sample. The data reported in the tables were the mean values and standard deviations. The IAEA reference value and the acceptable range are listed for comparison purposes at the bottom of each table.

TABLE I-1. LIST OF EXPERTS PARTICIPATING IN THE CRP

Participant	Organization[a]
D.L. Deb	Indian Agricultural Research Institute, Nuclear Research Laboratory, New Delhi, India
M. Fathony	Badan Tenage Atom Nasional, Pusat Standardisasi and Keselamatan Radiasi, Jl Cinere Pasar Jumat, Indonesia
Y.P. Hong, B.C. Jang	National Institute of Agricultural Science and Technology, Korea
S.Y. Lai	Taiwan Radiation Monitoring Center, Taiwan, China
A.S. Mollah	Atomic Energy Research Establishment, Institute of Nuclear Science and Technology, GPO, Bangladesh
N.T.Ngo and N.T. Binh	Nuclear Research Institute, Center for Analytical Techniques and Environmental Research, Vietnam
W.L. Robison	Lawrence Livermore National Laboratory, Marshall Islands Dose Assessment and Radioecology Program, United States of America
F. Sinakhom	Office of Atomic Energy for Peace, Thailand
V Skarlou-Alexiou	National Centre for Scientific Research "Democritos", Institute of Biology, Greece
S. Topcuoglu	Cekmece Nuclear Research and Training Center, Turkey
J.R. Twining	Australian Nuclear Science and Technology Organisation, Australia
S. Uchida	National Institute of Radioecological Science, Japan
M.A. Wasserman	Institute of Radiation Protection and Dosimetry, Brazil
T. Yassine	Syrian Atomic Energy Commission, Radiation Protection and Safety Department, Syria

[a] The affiliation of each participant for the duration of the CRP, 1993–1997.

TABLE I-2. RESULTS OF THE INTERCOMPARISON EXERCISE FOR THE REFERENCE SAMPLE IAEA SOIL 6

Participant	Activity concentration (Bq/kg DM)		
	Sr-90	Cs-137	Pu-239,240
Hong and Jang (Korea)	—[a]	48	—
Lai (Taiwan, China)	—	47	—
IAEA value (range)	30.4 (24.4–31.7)	53.7 (51.5–58)	1.04 (0.96–1.1)

[a] —: Data not available.

TABLE I-3. RESULTS OF THE INTERCOMPARISON EXERCISE FOR THE REFERENCE SAMPLE IAEA 375, SOIL

Participant	Activity concentration (Bq/kg DM)					
	Sr-90	Cs-134	Cs-137	Pu-238	Pu-239,240	Am-241
Deb (India)	—[a]	—	5123	—	—	—
Fathony (Indonesia)	—	—	4635 ± 87	—	—	—
Lai (Taiwan, China)	99.8	389 ± 8	4680 ± 141	—	—	—
Mollah (Bangladesh)	98.2 ± 8.6	—	5170 ± 109	—	—	—
Ngo and Binh (Vietnam)	103 ± 13	—	5308 ± 62	—	—	—
Robison (United States of America)	125 ± 12	463 ± 3	5028 ± 57	0.09 ± 0.01	0.36 ± 0.03	0.25 ± 0.04
Skarlou (Greece)	—	457 ± 30	5484 ± 55	—	—	—
Sinakhom (Thailand)	—	—	5077 ± 93	—	—	—
Topcuoglu (Turkey)	—	457 ± 13	5277 ± 2.0	—	—	—
Twining (Australia)	89 ± 2	—	5520 ± 26.2	—	—	—
Uchida (Japan)	—	—	5140 ± 216	—	—	—
Wasserman (Brazil)	—	456 ± 34	5363 ± 381	—	—	—
Yassine (Syria)	111 ± 10	—	4896 ± 161	—	—	—
IAEA value	108	463	5280		0.30	0.13
IAEA range	101–114	454–472	5200–5360		0.26–0.34	0.11–0.15

[a] —: Data not available.

TABLE I-4. RESULTS OF THE INTERCOMPARISON EXERCISE FOR THE REFERENCE SAMPLE IAEA 156, CLOVER

Participant	Activity concentration (Bq/kg DM)		
	Sr-90	Cs-134	Cs-137
Deb (India)	— [a]	—	258
Fathony (Indonesia)	—	—	197 ± 90
Hong and Jang (Korea)	—	138 ± 25	268 ± 3.3
Lai (Taiwan, China)	12.7 ± 3.0	122 ± 7.3	267 ± 27
Mollah (Bangladesh)	12.9 ± 1.7	—	251 ± 13.2
Ngo and Binh (Vietnam)	11.0 ± 2.0	—	268 ± 12
Robison (United States of America)	16 ± 2.0	134 ± 19	264 ± 2.1
Skarlou (Greece)	—	—	278 ± 11
Sinakhom (Thailand)	—	—	307 ± 36
Topcuoglu (Turkey)	—	—	244 ± 16
Twining (Australia)	13 ± 1	—	279 ± 4.8
Uchida (Japan)	—	—	285 ± 15
Wasserman (Brazil)	—	—	313 ± 23
Yassine (Syria)	13.3 ± 3.0	—	256 ± 23
IAEA value (range)	14.8 (13.4–16.3)	132 (126–138)	264 (254–274)

[a] —: Data not available.

TABLE I-5. RESULTS OF THE INTERCOMPARISON EXERCISE FOR THE REFERENCE SAMPLE IAEA SL3, LAKE SEDIMENT

Participant	Activity concentration (Bq/kg DM)				
	Sr-90	Cs-137	Pu-238	Pu-239,240	Am-241
Deb (India)	— [a]	0.15	—	—	—
Lai (Taiwan, China)	3.1 ± 1.4	5.0 ± 0.4	—	—	—
Ngo and Binh (Vietnam)	3.5 ± 0.9	6.55 ± 0.97	—	—	—
Robison (United States of America)	2	5.8 ± 2.0	0.005 ± 0.002	0.19 ± 0.014	0.075 ± 0.009
Topcuoglu (Turkey)	—	3.5	—	—	—
Twining (Australia)	12 ± 3	4.1 ± 3.3	—	—	—
Uchida (Japan)	—	7.7 ± 1.5	—	—	—
Wasserman (Brazil)	—	4 ± 0.81	—	—	—

[a] —: Data not available.

TABLE I-6. RESULTS OF THE INTERCOMPARISON EXERCISE FOR REFERENCE SAMPLE IAEA V8, RYE FLOUR

Participant	Concentration (g/kg DM)	
	Ca	K
Fathony (Indonesia)	0.36	1.51
Mollah (Bangladesh)	0.14 ± 0.001	1.89 ± 0.2
Ngo and Binh (Vietnam)	0.15 ± 0.004	1.86 ± 0.07
Robison (United States of America)	0.15 ± 0.003	2.0 ± 0.1
Twining (Australia)	0.13	1.9
Uchida (Japan)	0.16 ± 0.025	1.67 ± 0.19
Wasserman (Brazil)	0.11 ± 0.01	1.8
IAEA value (range)	0.149 (0.139–0.159)	1.93 (1.79–2.06)

ANNEX II.

PROTOCOL ADOPTED FOR SOIL TO PLANT TRANSFER STUDIES AND DATA CORRELATIONS IN THE CRP[1] "TRANSFER OF RADIONUCLIDES FROM AIR, SOIL, AND FRESHWATER TO THE FOOD CHAIN OF MAN IN TROPICAL AND SUB-TROPICAL ENVIRONMENTS"

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II-1. DEFINITIONS AND CONCEPTS ADOPTED

Soil-to-plant transfer factor, TF (TF_{plant}) concept used in radiological dose assessments relate the radionuclide activity concentration in the soil (Bq/kg DM[2]) with that in the edible part of crops (Bq/kg DM) [II-1]. The *TF* value*s* can be based on the activity concentration of a radionuclide in soil or on its activity per unit area of soil.

In 1982, the International Union of Radioecology (IUR) standardized the rooting depth in the definition of TF. In the new definition it was assumed that all radioactivity in the actual rooting zone in the soil is present in a standardized rooting zone; set at 10 cm depth for grass, and 20 cm depth for all other crops (including fruit trees). The IUR definition was adopted within the CRP:

$$\mathrm{TF_{grass}} = \frac{\text{Activity concentration in grass } (\frac{\mathrm{Bq}}{\mathrm{kg}},\mathrm{DM})}{\text{Activity concentration in upper 10 cm of soil } (\frac{\mathrm{Bq}}{\mathrm{kg}},\mathrm{DM})} \quad \text{(II-1)}$$

$$\mathrm{TF_{crop}} = \frac{\text{Activity concentration in crop } (\frac{\mathrm{Bq}}{\mathrm{kg}},\mathrm{DM})}{\text{Activity concentration in upper 20 cm of soil } (\frac{\mathrm{Bq}}{\mathrm{kg}},\mathrm{DM})} \quad \text{(II-2)}$$

The (estimated) rooting depth was recorded so that TF could be calculated using a variety of different approaches.

During pot experiments, the activity concentration in the soil would be reported if pots with a depth of less than 20 cm were used as a recalculation to a depth of 20 cm was not recommended. For pots that were more than 40 cm deep a rooting depth of 40 cm was assumed. In this case TF were recalculated assuming that all of each studied radionuclide was present in the upper 20 cm layer.

The TF can also be defined in terms of the surface area using the ratio:

$$\mathrm{TF_{crop}} = \frac{\text{Activity concentration in crop } (\frac{\mathrm{Bq}}{\mathrm{kg}},\mathrm{DM})}{\text{Activity concentration in surface area of soil } (\frac{\mathrm{Bq}}{\mathrm{m^2}})} \quad \text{(II-3)}$$

This definition avoids the problem of having to take the rooting depth into account. Conversion between the two definitions can be carried out for both field and lysimeter experiments by measuring or estimating the soil bulk density. However, the conversion is difficult to apply for pot experiments.

[1] CRP: Coordinated Research Project.
[2] DM: dry mass.

An alternative approach, often used in the 1960s and 1970s, was based on the assumption that the ratio of plant available caesium to potassium in soil is proportional with the ratio of caesium to potassium in the crop. Because the potassium content in a selected crop is approximately constant, the activity concentration of ^{137}Cs in crops can be calculated from:

$$^{137}\mathrm{Cs}_{\mathrm{crop}} = \mathrm{K}_{\mathrm{crop}}\left(\frac{^{137}\mathrm{Cs}}{\mathrm{K}}\right)_{\mathrm{soil}} \qquad \text{(II-4)}$$

The method is less precise as discrimination between caesium and its analogue, potassium, can occur in biological systems. Furthermore, the ratio in soil refers to bioavailable caesium and potassium. An approximation of the bioavailability of Cs and K at that time could be made by extracting potassium or caesium using 1N ammonium acetate (pH = 7), soil-to-soil solution ratio 1:10 with a shaking period of about 5 minutes [II-2]. The same considerations apply to strontium in combination with its analogue, calcium.

The definitions of TF imply that there is equilibrium between the radionuclides in the soil and those in the crops. This is because the TF are mainly used in environmental models for the calculation of doses from routine radioactive discharges, which mostly assume that such an equilibrium situation has been established. Therefore, the experimental protocols carried out during the CRP were designed to ensure that equilibrium was reached.

II-2. ADOPTED EXPERIMENTAL PROTOCOL FOR THE DETERMINATION OF SOIL–TO–PLANT TRANSFER PARAMETERS

Choice of crop – Data were desired for the following crops:

(1) Watermelon, tomato, all tropical fruit;
(2) Tropical leafy vegetable, komatsuna (Japanese cabbage), Chinese cabbage;
(3) Chick bean, broad bean, soybean, black bean, peanut;
(4) Cassava, yam, taro;
(5) Sugar cane, tobacco, tea, spice; and
(6) Rice (dry and irrigated), sorghum, millet.

Cereals are one of the most important crop groups that are widely grown, and are mainly comprised of wheat, barley and rye in temperate climates, while rice and sorghum dominate in sub-tropical and tropical areas. The varieties chosen for the experiments would reflect normal agricultural practices that were representative of the region. Expert advice on agricultural practices would be consulted to make the appropriate choice where relevant. It was not recommended that participants from different countries use the same crop or variety to improve reproducibility or to pursue scientific interests.

Choice of soil – The soils selected would be representative of the cultivated area and selected crops. Soils would be described in two ways:

(i) According to their development. The FAO/UNESCO scheme was recommended [II-3], since this taxonomic system of classification of soil is followed in many countries. Participants from countries that do not use this system would seek expert advice – for example by consulting a specialist in soil sciences – to determine the type of soil within the FAO/UNESCO scheme.
(ii) According to their texture and composition, e.g. clay, sandy loam, peat.

It was recommended that the textural class of soil be determined by using the triangular diagram of the US Department of Agriculture (USDA) system, which is described in textbooks on soil science [II-4]. Particle size distributions would be determined using hydrometers standardized as per USDA specification.

Data on soil would also be reported using guidance on information that would be included as given below. These data are relatively easy to determine and provide a good basis for statistical analysis. The FAO/UNESCO classification system was considered insufficient to allow a statistical evaluation.

Type of experiment – Three experimental options, namely: field, lysimeter and pot were considered.

Field experiments provide more reliable results than other experiments. For example, experiments with lysimeter may underestimate the effect of adhering soil, as crops grown in a lysimeter can be affected by wind-blown uncontaminated soil originating from areas outside the lysimeter. However, field experiments require an area contaminated with radioactive material, which might be difficult to identify; in this case, the use of lysimeters was advised.

Pot experiments generally lead to higher uptakes than field or lysimeter studies because the smaller amount of soil used can improve the efficiency of the roots to absorb sufficient quantities of nutrients and, consequently, increase the uptake of radionuclides from the soil. The TF obtained with relatively small pots under greenhouse conditions were considered non-representative of field conditions and comparison with values obtained using different procedures was advisable. Consequently, it was recommended that larger pots containing at least 8 to 12 kg of soil be used as they provide more reliable data and reduce problems with water shortage and nutrient deficiency at the same time.

Repetitions and duration of the experiment – A minimum of three replicates was considered advisable to obtain reliable values; the number of repetitions would be increased if more than one transfer parameter is investigated. Experiments would be continued for as long a period as possible, and preferably determine uptake data for 3 successive growing periods. If an experiment was intended to study the decrease of the availability of radionuclides to the plant's uptake with time; a minimum period of five years was recommended. Crop rotation would be included in the experimental design if it was a common agricultural practice of the region for which TF are measured.

Selection of radionuclides – Data were required for radionuclides whose soil-to-plant transfer parameters are important for radiological dose assessments associated with the normal operation of nuclear power installations: notably ^{137}Cs, ^{90}Sr, ^{239}Pu. Other radionuclides that might be optionally included in the experiments were: iodine, americium, cobalt and zinc. There is no difference in ecological behavior between isotopes of the same element, such as ^{137}Cs and ^{134}Cs or ^{90}Sr and ^{85}Sr. Consequently, no preference was given regarding which isotope was used. However, differences in half-lives between different isotopes were taken into account. For example, the physical half-life of ^{85}Sr is short so it can only be used for one growing period. In experiments that cover more than one year, the initial activity of ^{85}Sr would be higher than ^{90}Sr, because of the relatively shorter half-life of ^{85}Sr.

Application of radionuclides – The amount of radionuclide to be used in the experiments would take account of a number of relevant factors, such as the uptake and yield, number of samples required and analytical sensitivity. The amount of radionuclide activity used in experiments would be sufficient to avoid long counting times for a large number of samples.

Number of radionuclides within the same experiment – The number of radionuclides that can be used in the same experiment may depend on the resolution of the detecting equipment. It is possible to perform experiments involving both strontium and caesium at the same time. In these experiments, it was recommended to use initially only one isotope of each element, to be able to use a different isotope to check differences of availability with time (e.g. ^{137}Cs to be used first and ^{134}Cs after 2 years). It was advised to carry out plutonium and americium studies in separate experiments, as mixing americium and plutonium with other nuclides complicates the chemical separation.

Time of soil labelling – The adsorption of radionuclides by soil may be a fast process in which equilibrium between radionuclides in the soil-solution phase and the soil phase is reached within one to three months after the application of most radionuclides. Radionuclides, and in particular caesium, would therefore be applied to the soil at least two months before sowing, while for strontium one month was sufficient.

Uptake experiments that consider a short contact time between soil and radionuclide were not considered very useful. In this case, direct contamination of the already grown crop may have occurred, which would exceed radionuclide uptake from soil as the gradual adsorption of radionuclides by soil with time, referred to as "fixation" or sometimes "ageing", occurs at a much slower rate.

Labelling methods – Two methods can be used to label a soil:

(1) The tracer is applied by spraying as a solution.

This method is simple, but considerable care would be taken to avoid any loss of the labelled solution through cracks in the surface soil. The application would be carried out before the experimental vegetation was growing to avoid uptake via leaves. The uniformity would be checked by a thorough sampling procedure.

Carrier-free radionuclides would be avoided. It was recommended to add stable carrier to the radionuclide to avoid the adsorption of carrier free radionuclides to the wall of vessels used during soil labelling. The stable carrier limits unwanted adsorption on vessel walls, and also prevents the adsorption of the entire label onto the first soil particles with which the radionuclides come into contact. The amount of carrier nuclide would be low compared to that of stable nuclides, which are naturally present in the soil.

In tree experiments, when large pots are used, the tracer could be applied as a solution by spraying small droplets of tracer solution on several layers of soil, each about 2 cm thick. Subsequent watering encouraged a uniform distribution of activity in the large pots.

(2) Soil is sampled and the radionuclide is added to the soil in a mixer to provide a homogenous soil-label system.

This method is recommended for soils that can be easily mixed. The method is difficult to use with clay soils, depending on the moisture content of the soil. Two methods can be used in the analysis:

Premix method: A premix is prepared in a kitchen mixer consisting of 1.5–2.0 kg of soil and 8–10 ml of an aqueous solution of the radionuclides which is distributed over the soil with a pipette. The premix is added to 50–60 kg of soil with a soil-water content of about 3–5% and mixed in a concrete mixer. The activity concentration of sub-samples has a standard deviation typically of about 30%.

Direct method: This is a laborious method. The soil from the top 5 cm layer is dried, ground and mixed with a radionuclide solution in a concrete mixer so that the water content of the corresponding soil-water mixture is about 50% of the saturation value. Good results can also be obtained by drying the soil to 5–15% water content, then adding another 5% of water by spraying the radionuclide solution onto the soil in a concrete mixer. A mixing time of 5 minutes is sufficient: longer mixing may produce small accumulation of higher activity. A standard deviation of the radionuclide activity concentration of sub-samples of about 10% can be reached.

It was recommended that the selected method be tested using stable elements to ensure it worked before using a tracer.

Surface runoff – Surface runoff can occur during high rainfall or flooding and could prejudice the experiment. Precautions were required to avoid the production of surface runoff shortly after labelling by spraying.

Sampling of soil – Sampling was required to check the initial homogeneity of the radionuclide distribution and to determine the amount of radioactivity actually present in the rooting zone As noted in the IUR protocol (above) the rooting zone was defined as 10 cm for grasses and 20 cm for all other crops. Migration velocities in soil are usually of the order of only a few millimeters per year.

In pot or lysimeter studies soil cores would be collected to the depth of the root zone. This can be done by increments of 5 cm or 10 cm or as a composite in the entire depth of the root zone. In field studies, soil could be collected in 5 cm or 10 cm increments or as integrated cores through the depth of the root zone. Coring holes would be refilled with inert material and the holes marked.

For the analysis of short-lived radionuclides, the soil would always be sampled at the time of harvest.

Crop production – To ensure that TF are realistic, it was important that crops are produced according to local agricultural practice. The selection of varieties, and the methods used for fertilization, irrigation and pest treatment, would follow local procedures. If manure is required, it would be tested for ^{137}Cs and a correction to the ^{137}Cs content of the soil would be applied if necessary.

Harvest and sampling of crop – In general, only TF to the edible part of the crop or the part of the plant that is usually consumed would be determined. Other parts of the plant can be included at the discretion of the investigator. It is not required that the crop product be processed, cooked or treated in any way. If samples are washed, plain water without detergent would be used. Grasses that are used as animal feed would not be washed. It would be interesting, however, to determine the radionuclide activity concentration with and without washing.

If possible, samples would be collected over a three-year period and annual values reported. The annual variation is expected to be large. Samples would be collected at maturity or at the stage at which the crop is normally harvested for consumption. The frequency of collection is generally dictated by plant species (usually once or twice a year).

The uptake of plutonium and americium via the plant root is very low with TF ranging from the order of 1×10^{-6} to 1×10^{-5} (Bq/kg DM crop)/(Bq/kg DM soil in the top 20 cm layer). When TF for these elements are determined, care is needed to avoid the adhesion of soil to the fruit or plant leaves, since the contamination of a crop due to adhering soil may easily dominate the

plant physiological uptake via the roots. A contamination of only 1 mg soil per kg FM crop – equivalent to about 10 mg soil per kg DM crop – causes an apparent TF of 1×10^{-5}.

Additional information – The spread of values of soil to plant transfer is caused by the great variation of ecological conditions which exist in nature and agricultural practice. It is important to know in what way these various conditions influence the uptake. Documentation of the experimental conditions was therefore required. The following parameters were considered essential for the interpretation of the uptake values:

(a) pH (in KCl or $CaCl_2$) or in water;
(b) Organic matter content (not the carbon content);
(c) Exchangeable potassium, for studies involving caesium, and calcium, for studies involving strontium, in soil milli-equivalents/100 g;
(d) Moisture content of crop before drying;
(e) Time of labelling of the soil (year and month);
(f) Time of harvest (year and month);
(g) Contents of potassium, for studies involving caesium, and calcium, for studies involving strontium, in crop (mg/kg DM); and
(h) Rooting depth (cm).

Other parameters which might be useful are (in order of importance):

(1) Water surplus or water shortage, which is the sum of rainfall and irrigation minus evapotranspiration (mm/y);
(2) Growing period of crop (GRT in months);
(3) Clay content of soil;
(4) Type of clay minerals; and
(5) Cation Exchange Capacity of soil (CEC) (milli-equivalent/100 g soil).

Several methods exist to determine the CEC and exchangeable cations in soils. The recommended method is suitable for the interpretation of uptake experiments. Fairly accurate measurements of the CEC and exchangeable cations can be obtained by the method described by Schollenberger and Simon [II-5] in non-calcareous soils. However, special care is required for soils containing $CaCO_3$ or $MgCO_3$. Calcium and manganese ions go into solution during extraction by ammonium acetate. A correction for the amount of Ca and Mg extracted from soil carbonates is required for the calculation of exchangeable calcium and manganese. Neither CEC nor exchangeable calcium and manganese values are very accurate for calcareous soils even after correction. [II-6]. For calcareous soils, the recommended method to determine CEC and exchangeable cations is the extraction of soil with 0.2 N $BaCl_2$ – triethanolamine (pH: 8.1) because it requires no correction and gives a more reliable estimate of exchangeable calcium and manganese CEC [II-7].

Sample preparation – A good registration system during sample collection and subsequent analysis is essential and the use of a logbook to this purpose is recommended. If samples are freeze dried, lysis may occur resulting in radionuclide adsorption on the vessel walls. The vessel wall would, therefore, be rinsed thoroughly after thawing and the rinsing liquid collected.

Analysis – The analysis of samples is beyond the scope of this protocol. However, an adequate quality assurance program would be implemented. The counting equipment would be routinely calibrated and checked with standard samples. The following procedures would be considered:

(1) Blinds standards and duplicates (10% of samples submitted for analysis);
(2) Facility Quality Control;
(3) Traceable standards;
(4) Daily calibration and weekly calibration of entire sample routine (gamma spectroscopy);
(5) Backgrounds (weekly for gamma spectroscopy);
(6) Spikes and blanks (radiochemistry).

It was recommended to report both the derived TF and associated data such as pH, exchangeable potassium, separately as it enables analysis of causal factors affecting variation in TF. Moreover, reporting of mean values alone can may prevent analysis of the influence of these factors.

II-3. SUMMARY AND DISCUSSIONS OF CRP DATA

The TF for the edible parts of crops were determined within the CRP, since these parameters are intended to be used in radiological dose assessment models. Several participants included TF for plant parts other than those specific for the edible products in their studies. Data on activity concentrations and TF for different parts of fruit trees as a function of time after contamination, can help to determine the contribution of radionuclides stored in different parts of the tree to the radionuclide content of fruit. Similarly, radionuclide transfer from the stem and leaves of the cereal crop may facilitate prediction of the TF for grains of cereal crops.

Participants to the CRP were asked to conduct field experiments preferentially over lysimeter or pot experiments. However, only a limited number of field experiments could be carried out and most investigators conducted lysimeters or pot studies. The use of pots enabled comparisons of the uptake from several different soils under the same experimental conditions. The results of such experiments were considered with care, since the TF derived from pot studies may be higher than those determined in field conditions [II-8].

The radionuclides that were used in most of the experiments were: ^{137}Cs, ^{85}Sr and ^{90}Sr. Some investigators included ^{134}Cs, whilst others included one or more isotopes of iodine, technetium, cobalt, zinc, plutonium or americium.

In all experiments the crop and crop variety, type of soil, type of management, and other environmental conditions were selected to reflect, as closely as possible, the natural conditions and agricultural practices of the country. Table II-1 provides information on the range of TFs which were determined or collected during the CRP in each participant country.

II-3.1. The impact of the ionic soil matrix and nutrient status

The ionic composition of the soil solution and the presence of exchangeable nutrient ions have a large influence on crop production. Soil chemistry will also influence the uptake of radionuclides. The similarities of chemical behaviour between caesium and potassium and strontium and calcium are also observed in plants. The uptake of caesium and strontium is lower from soils with high concentrations of potassium or calcium because of dilution effects. For example, at the IUR's 1992 Workshop on Soil to Plant Transfer, Shutov [II-10] presented an analysis of the impact of environmental conditions on the uptake of radiocerium by grass in the former Soviet Union after Chernobyl accident, in which Ln(TF(Cs)) was highly correlated to Ln(K).

TABLE II-1. SUMMARY OF DATA ON SOIL-TO-PLANT TRANSFER FACTORS COLLECTED WITHIN THE CRP

Element	Participant[a]	Source	Cereals	Pod	Root	Tuber	Gr. veg.	Fruit	Herb	Other[b]
Americium	Robison (Marshall Isl.)	Experiment						√		
Cobalt	Lai (Taiwan, China)	Experiment					√			√
	Ngo (Vietnam)	Experiment	√	√	√	√	√	√		
	Uchida (Japan)	Experiment	√	√	√		√			
	Wasserman (Brazil)	Experiment			√					
	Various participants	Literature search	√		√	√	√	√		
Caesium	Deb (India)	Experiment	√	√						
	Fathony (Indonesia)	Experiment	√	√						
	Lai (Taiwan, China)	Experiment	√		√		√		√	√
	Mollah (Bangladesh)	Experiment	√	√			√	√		√
	Ngo (Vietnam)	Experiment	√	√	√	√	√	√	√	
	Robison (Marshall Isl.)	Experiment								
	Skarlou (Greece)	Experiment	√	√	√			√		√
	Topcuoglu (Turkey)	Experiment	√	√				√	√	√
	Twining (Australia)	Experiment	√	√				√		√
	Uchida (Japan)	Experiment	√	√	√		√			
	Wasserman (Brazil)	Experiment		√	√					
	Yassine (Syria)	Experiment	√	√			√			
	Avila (Cuba)	Literature search					√	√		
	Various participants	Literature search	√		√	√	√	√		
	Consultant (Iraq)[c]	Literature search	√	√	√	√	√	√		
Iodine	Uchida (Japan)	Experiment	√	√			√			
	Osores (Peru)	Literature search		√						
	Various participants	Literature search	√		√	√	√	√		
Manganese	Lai (Taiwan, China)	Experiment								√
	Uchida (Japan)	Experiment	√	√	√		√			
Lead	Wasserman (Brazil)	Experiment	√	√						
	Twining (Australia)	Literature search								√
	Wasserman (Brazil)	Literature search	√	√	√	√	√	√		
Plutonium	Robison (Marshall Isl.)	Experiment						√		
	Various participants	Literature search	√		√	√	√	√		
Radium	Wasserman (Brazil)	Experiment	√	√						
	Twining (Australia)	Literature search								√
	Wasserman (Brazil)	Literature search	√	√	√	√	√	√		
Strontium	Deb (India)	Experiment	√	√						
	Fathony (Indonesia)	Experiment	√	√						
	Hong and Jang (Korea)	Experiment	√							
	Lai (Taiwan, China)	Experiment	√		√					
	Mollah (Bangladesh)	Experiment	√	√			√			√
	Ngo (Vietnam)	Experiment	√	√	√	√	√	√		
	Robison (Marshall Isl.)	Experiment						√		
	Skarlou (Greece)	Experiment	√	√	√		√	√		√
	Uchida (Japan)	Experiment	√		√		√			√
	Yassine (Syria)	Experiment	√	√			√	√		
	Avila (Cuba)	Literature search	√	√	√	√	√	√		
	Various participants	Literature search	√		√	√	√	√		
Technetium	Uchida (Japan)	Experiment	√	√	√		√			
Thorium	Twining (Australia)	Literature search								√
	Wasserman (Brazil)	Literature search	√	√	√	√	√	√		
Uranium	Wasserman (Brazil)	Experiment	√	√						
	Various participants	Literature search	√	√	√		√	√		
	Twining (Australia)	Literature search								√
Zinc	Deb (India)	Experiment	√							
	Ngo (Vietnam)	Experiment	√	√	√	√	√	√		
	Uchida (Japan)	Experiment	√	√			√			

[a] Experts participating in the CRP (see also Table I-1 from Annex I above).
[b] Grass, fodder, water lilies, mushrooms.
[c] Data from Ref. [II-9].

TABLE II-2. REGRESSION ANALYSIS OF TRANSFER FACTORS OF CS AND SR AS A FUNCTION OF EXCHANGEABLE K AND CA, RESPECTIVELY

Crop	R^2	$Ln(TF_0)$[a]		X-coefficient[a]		$Ln(TF_{min})$[b]	$Ln(TF_{max})$[b]	TF_{max}/TF_{min}
		Value	Standard deviation	Value	Standard deviation			
				Ln(TF(Cs)) vs K				
Cereals	0.06	-4.14	1.46	-1.19	0.60	-4.17	-6.04	6
Pods, beans	0.45	-1.68	1.33	-2.07	0.33	-1.92	-5.18	2.6
Green vegetables	0.10	-2.67	1.48	-1.41	0.03	-2.71	-4.94	9
Fruit [c]	0.45	-0.34	2.55	-5.25	0.66	0.18	-0.06	3 830
All crops [d]	0.11	-3.18	1.66	-1.37	0.28	-3.22	-5.38	9
				Ln(TF(Cs)) vs Ln(K)				
Cereals	0.17	-5-52	1.37	-0.76	0.11	-3.07	-5.73	14
Pods, beans	0.53	-4.23	1.22	-0.88	0.12	-1.14	-4.64	33
Green vegetables	0.05	-3.90	1.52	-0.49	0.42	-2.17	-4.14	7
Fruit [c]	0.76	-5.45	1.68	-2.23	0.14	2.4	-6.5	97 000
All crops [e]	0.47	-5.11	1.93	-1.50	0.11	0.14	-5.82	390
All crops [d]	0.64	-5.36	1.97	-1.96	0.09	1.51	-6.28	2 400
Grass	— [f]	—	—	—	—	-1.71	-5.68	53
				Ln(TF(Sr)) vs Ca				
Cereals	0.01	-1.72	0.96	-0.16	0.17	-1.72	-2.25	2
Pods, beans	0.06	0.40	1.43	-0.59	0.42	0.40	-1.52	7
Green vegetable	0.50	3.15	0.69	-0.91	0.23	3.16	0.21	19
				Ln(TF(Sr)) vs Ln(Ca)				
Cereals	0.05	-1.68	0.95	-0.05	0.02	-1.73	-2.96	4
Pods, beans	0.01	-0.57	1.47	-0.04	0.05	-0.16	-1.45	2
Green vegetables	0.38	2.28	0.76	-0.10	0.03	2.17	-0.30	12

[a] $Ln(TF_0)$ is the calculated hypothetical value of Ln(TF) for zero concentrations of potassium or calcium, while X-coefficient is the slope of the correlation, with the intercept given by the value of $LN(TF_0)$.
[b] Ln(TFmin) and Ln(TFmax) refer to hypothetical TF for minimum and maximum concentrations of potassium or calcium, expected in the majority of soils. For potassium these values are 0.03 and 1.6 milli-equivalent/100 g soil and for calcium they are 1 and 25 milli-equivalent/100 g soil.
[c] All fruits, excluding coconuts and copra.
[d] All crops, including coconuts and copra.
[e] All crops, excluding coconuts and copra.
[f] —: Data not available.

Sufficient data were gathered during the CRP to test such correlation for four crop groups: cereals, pods and beans, green vegetables and fruit. The correlation with exchangeable potassium and calcium and the logarithm of this quantities were analyzed and the results are shown in Table II-2.

The data in Table II-2 (data available at March 1, 1997) show that the correlations between the logarithms of the TF of caesium and strontium and of exchangeable potassium and calcium, are slightly better than those without logarithms. The use of logarithms, however, increases the ratio between the hypothetical minimum and maximum TF, although this is likely to be an artefact of the extrapolation. The ratios between the hypothetical maximum and minimum TF is a measure of the range which can be expected at zero concentrations of potassium or calcium. The use of concentrations of exchangeable potassium and calcium, which can be readily measured, seems to give more reliable results. In general, the typical range of concentrations of exchangeable potassium and calcium observed is about a factor of 10. Consequently, the uncertainty in the prediction of TF can be reduced by about a factor of 10. However, the uncertainty in the TF still remains high, as seen by the standard deviation for $Ln(TF_0)$ which is the hypothetical TF for zero concentrations of exchangeable potassium and calcium in the fourth column of Table II-2, which on average is 1.5.

TABLE II-3. AVERAGE TRANSFER FACTORS OF STRONTIUM AND CAESIUM FOR CABBAGE AND CEREALS

Investigator [a]	Transfer factor (Bq/kg DM)/(Bq/kg DM, 20 cm top layer) [b]		Ratio cabbage / cereals
	Cereals	Cabbage	
	Strontium		
Stoutjesdijk, Netherlands (IUR database) [c]	0.14	3.6	26
Steffens, Germany (IUR database) [c]	0.25	3.6	81
Yassine, Syria	0.041	2.7	55
Uchida, Japan	0.050	1.4	40
Ngo, Vietnam	0.093	2.3	25
Mollah, Bangladesh	0.59	1.5	2.5
TRS 364 [II-1] (95% confidence range)	0.022–0.66 clay, loam 0.032–1.4 sand 0.002–0.20 peat	0.74–10 clay, loam 0.3–30 sand 0.026–2.6 peat	
	Caesium		
Lai, Taiwan, China	0.001 7	0.012	1.7
Yassine, Syria	0.003 2	0.015	49
Haisch, Germany (IUR database) [c]	0.005	0.045	8.2
Steffens, Germany (IUR database) [c]	0.007	0.16	22
Stoutjesdijk, Netherlands (IUR database) [c]	0.008	0.054	6.6
Grogan, UK (IUR database) [c]	0.020	0.051	2.6
Cawse, UK (IUR database) [c]	0.095	0.29	3.0
Uchida, Japan	0.014	0.71	52
Ngo, Vietnam	0.093	1.3	14
Mollah, Bangladesh	0.17	1.1	6.6
Robison, Marshall Islands	2.1	28	3.4
TRS 364 [II-1] (95% confidence range)	0.001–0.1 clay, loam 0.002 6–0.26 sand 0.008 3–0.83 peat	0.019–1.7 clay, loam 0.047–4.5 sand 0.025–2.7 peat	

[a] Experts participating in the CRP, defined by the group leader (see Table I-1 from Annex I and Table II-1 above).
[b] Geometric mean.
[c] The 'IUR database' from which these data were taken is no longer available at the time of publication of this publication.

II-3.2. Relationship between crop groups

Some radiological impact assessments require the experimental determination of the TF of all crops produced in a specified area. An alternative approach, based on relative TF values for different crops, may provide a faster, more reliable result. An examination of the data collected for the CRP shows that for a given radionuclide activity concentration in soil, the radionuclide activity concentration in cereals is always lower than for all other crops, while the radionuclide activity concentration in leafy products such as spinach, cabbage and grass are always higher. This applies both to caesium and strontium, although the patterns may differ for both radionuclides. It might therefore be the case that it is possible to work out a scheme to predict the radionuclide activity concentration of most crops from the TF of two or three "indicator crops" such as cereals and cabbages. Table II-3 compares the mean TF of strontium and caesium for cereals and cabbage. The TF of the "deviating systems" studied by Robison and Skarlou are not included in Table II-3. The mean value for cabbage derived from Uchida's data is based on three values, which show a large spread. Each of Mollah's values is only based on two observations, but the ratio between cabbage and cereals is again more stable than the individual TF values.

II-3.3. Comparison of TF for pot and field experiments

The TF of caesium in fruits determined by Robison in the Marshall Islands are shown in Table II-4. All observations were made for the same coral soil. Although the number of observations for squash, an annual crop, was low compared with those for tree crops, there appeared to be no systematic difference between the TF for fruit of annual and tree crops.

Within the CRP, some investigators, for example Skarlou (see Annex XII below), concluded from additional measurements made, that the radionuclide activity concentration in tree wood played no significant role in the contamination of fruit. In contrast, Robison (see Annex X below) reported that the contamination of the stem of a palm tree played a significant role in the contamination of coconuts, and Topcuoglu (see Annex XIII below) observed that the contamination of tea leaves might partly be caused by radiocerium already present in the tree.

II-3.4. Lead, radium, thorium and uranium

The TF data derived for lead, radium, thorium and uranium are reported in Table II-5.

TABLE II-4. TRANSFER FACTORS OF CAESIUM FOR FRUIT FROM THE MARSHALL ISLANDS

Type of crop	Variety	No. of observations	Transfer factor	
			Range	Geometric mean
Annual crop	Squash	10	0.73–9.7	2.9
Tree crops	Banana	5	0.13–0.58	0.32
	Breadfruit	8	0.22–3.7	1.0
	Papaya	23	1.0–31	5.9
	Coconut	107	1.4–32	6.4
	Pandanus	9	5.5–41	17

TABLE II-5. SOIL-TO-PLANT TRANSFER FACTORS FOR LEAD, RADIUM, THORIUM AND URANIUM COLLECTED DURING THE CRP COMPARED WITH PREVIOUS IUR DATA AND IAEA TRS 364 [II-1] VALUES

Isotope	Crop	TF from CRP		TF IUR database [a]		TRS 364 TF values		
		Participant [b]	Value [c]	Minimum	Maximum	expected	95% conf. range	
Pb-210	Terrestrial plants	Twining	0.25	0.000 5	0.2	— [d]	—	—
	Cereals	Wasserman	0.002 7	0.000 24	0.006	0.004 7	0.000 47	0.047
	Beans	Wasserman	0.041	0.001 4	0.035	—	—	—
Ra-226	Aquatic plants	Twining	2	—	—	—	—	—
	Grasses, shrub	Twining	1	0.02	0.4	0.08	0.016	0.4
	Cereals	Wasserman	0.005 6	0.000 24	0.006	0.001 2	0.000 24	0.006
	Beans	Wasserman	0.066	0.001 4	0.035	0.007	0.001 4	0.035
Ra-228	Cereals	Wasserman	0.004 5	0.000 24	0.006	0.001 2	0.000 24	0.006
	Beans	Wasserman	0.028	0.001 4	0.035	0.007	0.001 4	0.035
Th-228	Shrub	Twining	0.9	0.001	0.2	—	—	—
Th-230	Shrub	Twining	0.9	0.001	0.2	—	—	—
Th-232	Shrub	Twining	0.05	0.001	0.2	—	—	—
U-234	Aquatic plants	Twining	4.2	—	—	—	—	—
U-235	Shrub	Twining	0.01	0.002	0.2	—	—	—
U-238	Aquatic plants	Twining	2.6	—	—	—	—	—
	Cereals	Wasserman	0.001 7	—	—	0.008 3	0.000 83	0.083
	Beans	Wasserman	0.003 3	—	—	—	—	—

[a] The 'IUR database' from which these data were taken is no longer available at the time of publication of this publication.
[b] List of CRP groups, defined by their group leader, can be found in Table I-1 from Annex I and Table II-1 above.
[c] Geometric mean.
[d] —: Data not available.

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ANNEX III.

PROTOCOL ADOPTED FOR FRESHWATER TO FISH STUDIES AND DATA CORRELATIONS IN THE CRP[1] "TRANSFER OF RADIONUCLIDES FROM AIR, SOIL, AND FRESHWATER TO THE FOOD CHAIN OF MAN IN TROPICAL AND SUB-TROPICAL ENVIRONMENTS"

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III-1. CONCEPTS ADOPTED

The approach adopted for freshwater was designed to assess TF equilibrium values. It was anticipated that equilibrium would take time to establish as water activity concentrations can be highly spatially and temporally variable. Hence, uptake and loss were considered together. It was assumed that the time-dependent radionuclide activity concentration in fish is related to the activity concentration in water through an exponential equation of the type:

$$Q(t) = Q_{eq}(1 - e^{-\lambda t}) \quad \text{(III-1)}$$

where:

Q(t) is the radionuclide activity concentration in fish (Bq/kg FM[2]) at time t;
Q_{eq} is the radionuclide activity concentration in fish in Bq/kg FM at equilibrium, and;
λ is the rate coefficient given by the equation:

$$T_{1/2} = \frac{ln2}{\lambda} \quad \text{(III-2)}$$

where:

$T_{1/2}$ is the biological half-life, and
Q_{eq} can be expressed as:

$$Q_{eq} = TF\ x\ C \quad \text{(III-3)}$$

TF is the concentration factor at equilibrium in L/kg FM and C is the activity concentration in water at steady state in Bq/L.

Figure III-1 illustrates the relationship for an uptake period of 30 days and a release period of 54 days. The biological half-life in the example shown is 24 days, both for uptake and release. Such a curve can easily be fitted mathematically to experimental measurements.

III-2. PROTOCOL ADOPTED FOR FRESHWATER TO FISH STUDIES

The objective of the aquatic CRP studies was the derivation of TF for freshwater to fish, measured under experimental conditions that both reflected the natural environment and equilibrium conditions. The studies needed to be well defined with respect to those variables that could be expected to alter TF. The description of the environmental conditions is an important aspect to be considered, given both the great variation in freshwater environments and transfer pathways for different species of freshwater fish.

Choice of radionuclides – See protocol for soil to plant transfer in Annex II of this Supplementary File.

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[1] CRP: Coordinated Research Project.
[2] FM: Fresh Mass.

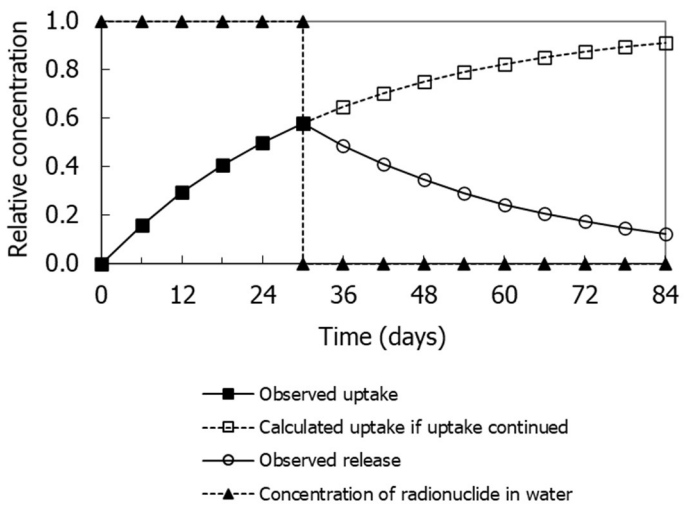

FIG. III-1. Example of uptake of a radionuclide by fish.

Choice of fish species – The species of fish selected would be common to the area, of dietary importance, and taxonomically identified to the species level. Examples were carp, sweet fish or crucian.

Biological experimental conditions – The following procedures would be applied:

- Acclimatisation: fish used in the experiment would be left for 14 days in conditions identical to the experimental conditions, but without addition of radionuclides.
- Feeding regime: fish used in the experiment would be fed using commercial fish food (life or artificial) delivered at rates equivalent to 3 mg dry feed/gram fish/day to maintain condition of fish only. Food type would be matched to feeding behaviour of experimental species.
- Day/night regime: the day/night regime would be appropriate to tropical/subtropical region of interest.
- Size of fish: to test the effect of size on radionuclide equilibrium level in tissue, the size range of fish used in the experiment would be the maximum available.
- Tissue analysed: muscle tissue and other organs that are consumed by humans.

Experimental system – The experimental system would comply to the following requirements:

- Three identical 500 L drums would be used: one for acclimatisation and two for experimental exposure. Each tank should contain a sediment layer.
- A continuous flow system would be used to maintain a constant activity concentration of radionuclides in the tanks.
- Temperature in the tanks would be kept constant at 26°C using a thermostat system.
- Water chemistry: a simulated water quality which reflects the environment of interest or the natural water.
- The pH would be regulated using a pH controlling system.
- Moderate aeration would be maintained to avoid sedimentation of particulate matter from in the water column, as well as O_2 saturation.
- Radionuclide would be added via a continually mixed and acidified stock solution, using a peristaltic pump system.

Physico-chemical parameters to be measured – The following parameters would be measured:

- Radionuclide activity concentration in water (Bq/L), particulate matter and sediment (both Bq/kg, dry mass (DM));
- Concentration of potassium and calcium in water for caesium and strontium experiments respectively (mg/L);
- Temperature (°C), pH and O_2 concentration in water (mg/L), daily;

Experimental design and statistical analysis – The experiment would be designed to determine:

- The rate of uptake of radionuclides into fish muscle at a constant radionuclide activity concentration in water;
- The equilibrium tissue activity concentration of radionuclides;
- The biological half-life of radionuclides in fish muscle (The assumption of the presence of a biological half-life requires an exponential curve, which can be fitted mathematically.);

At least 3 fish would be sampled per sampling period. Six samplings at 5-day intervals, during both uptake and loss phases would be performed. During the loss phase fish would be transferred to the acclimatization tank to avoid sediment contamination, which may lead to a reduction of loss rates. A statistical method, such as a multiple regression technique, would be used to evaluate the effect of size on rates of uptake and loss.

Analysis – The analysis of samples is beyond the scope of this protocol (see also the relevant section from Annex II above).

Reporting results – As already indicated, reported values would be based on a calculated equilibrium from a non-linear regression analysis or an assumed equilibrium.

- Activity concentrations of radionuclides in tissue, both as Bq/kg DM and Bq/kg FM;
- Radionuclide activity concentration in filtered water (Bq/L);
- Suspended matter concentration in water (g DM/L);
- Activity concentration of radionuclides in sediment (Bq/kg DM);
- TF of radionuclide (Bq/kg FM)/(Bq/L);
- Summary of other measured parameters;

Data reporting – as adopted for soil-plant studies in Annex II above.

The use of a standard protocol amongst the participants was generally successful in obtaining reliable data. However, the final meeting of the CRP concluded that the standard protocol for the determination of TF from freshwater to fish was not consistently satisfactory. As with any research tool, some procedures in the protocol were more difficult to apply than others and some improvements were required. The components of the protocol which may need modification or improvement to suit the environments or species being studied were:

- Factors such as feeding rate and stocking density, which will be species dependent;
- The use of sediments and aeration was recommended. However, this can lead to problems with day-to-day observation of the conditions of the experimental animals;

TABLE III-1. SUMMARY OF DATA ON FRESHWATER-TO-FISH TRANSFER FACTORS COLLECTED WITHIN THE CRP

Element	Participant [a]	Source	Fish	Aquatic, non-fish	Reptiles
Caesium	Mollah (Bangladesh)	Experiment	✓		
	Ngo (Vietnam)	Experiment	✓		
	Sinakhom (Thailand)	Experiment	✓		
	Twining (Australia)	Experiment	✓		
	Various participants	Literature search	✓		
Iodine	Various participants	Literature search	✓		
Lead	Twining (Australia)	Literature search	✓	✓	✓
Polonium	Twining (Australia)	Literature search	✓	✓	✓
Radium	Twining (Australia)	Literature search	✓	✓	✓
Strontium	Mollah (Bangladesh)	Experimental work	✓		
	Ngo (Vietnam)	Experimental work	✓		
	Sinakhom (Thailand)	Experimental work	✓		
	Twining (Australia)	Experimental work	✓		
	Various participants	Literature search	✓		
Thorium	Twining (Australia)	Literature search	✓	✓	✓
Uranium	Twining (Australia)	Literature search	✓	✓	✓

[a] List of CRP groups, defined by their group leader, can be found in Table I-1 from Annex I and Table II-1 of Annex II above.

- The flow-through systems often lead to variability in the quantity of suspended solids over the period of the exposure due to wash out;
- The protocol implies an uptake period of 30 days. However, this would be extended until a trend towards an equilibrium activity concentration is observed in the uptake curve fitting the measured data which would improve the accuracy of TF assessment;
- The use of a single compartment uptake model is recommended for simplicity. However, a multi-compartmental model may be more appropriate when the observed biological half-life differs from the modelled value. The observed value would be reported in preference to the modelled value;

The use of stepwise multiple regression analysis was also strongly recommended to identify the influence of any of the measured parameters on the TF. The regression analysis would not be restricted to size as indicated in the basic protocol.

III-3. SUMMARY AND DISCUSSIONS OF CRP DATA

Freshwater-to-fish TF for caesium, strontium and a number of other elements, collected within the CRP by experiment or literature review are summarised in Table III-1.

The data from the CRP on Cs and Sr accumulation in tropical freshwater fish species were combined with those of Srivastava et al. [III-1, III-2] and cited in [III-3]. The interim CRP reports containing the original data are no longer available. However, summaries of the country reports, encompassing the relevant data, are available in Annexes VII, VIII, XI and XIV below. When all eight experimental results were combined, the mean equilibrium TFs for Sr and Cs in tropical fish were markedly lower, by about an order of magnitude, than the expected values reported in IAEA TRS 364 (Table III-2) [III-4]. This was valid even after accounting for the dissolved concentrations of potassium and calcium (essential nutrients that at increasing concentrations suppress the uptake of any analogous monovalent or divalent cations). Similarly, the effect of suspended solids, which can complex with dissolved radionuclides to reduce apparent TF values, was insufficient to

account for the lower than expected values. The TF of lead, polonium, radium and uranium from freshwater to various animals determined by literature review of publications between 1974 and 1990 are reported in Table III-3. Data for fish for all elements are compared with values provided in IAEA TRS 364 [III-4]. The TF for lead determined in the CRP is below the range given in IAEA TRS 364, while the values for polonium and uranium are higher. Only the TF for radium obtained during the CRP is within the expected range provided in IAEA TRS 364. These results, together with the discrepancies for Cs and Sr noted previously, confirmed the need for additional studies to determine aquatic TF in tropical regions.

TABLE III-2. COMPILATION OF MEASURED AND MODELLED CS AND SR TRANSFER FACTORS TO FRESHWATER FISH IN TROPICAL ENVIRONMENTS AND MODELLED BIOLOGICAL HALF-LIVES [a]

Species	Size (SL [b] or mass)	Cs-137			Sr-85/90			Water parameters used for modelling				Notes	Reference
		TF modelled [c] L/kg (FM)	TF measured L/kg (FM)	$T_{1/2}$ (days)	TF modelled [d] L/kg (FM)	TF measured L/kg (FM)	$T_{1/2}$ (days)	Temp. (°C)	K^+ (mg/L)	Ca^{2+} (mg/L)	Suspended solids (mg/L)		
Zebrafish *(Brachidanio rerio)*	0.24 g	1015	16	51	—[f]	—	—	26	2.7	—	Nil	Whole fish	[III-1]
Goldfish *(Carassius auratus)*	2-6 g	1015	4	19	—	—	—	28	2.7	—	Nil	—	[III-2]
Tilapia *(Tilapia sp.)*	30-40 g[e]	—	26	12	—	—	—	—	—	—	—	—	data resulted from the CRP
Carp *(Cyprinus carpio)*	10-30 g	—	40	31	—	—	—	—	—	—	—		
Catfish *(Clarias sp.)*	160-270 g	59	4	29	—	—	—	27	29	67	100	Flesh and skin	data resulted from the CRP
		106	2	36	1	5	39	26.5	13	42	—	Whole fish	
		72	3	41	2	0.1	4	29.6	22	64	—	Flesh	
Singhi *(Heteroneustus fossils)*	22-24 cm	—	6	93	—	10	62	—	—	—	—	Flesh	data resulted from the CRP
Magur *(Clarias batrachus)*	20-25 cm	175	7	94	37	11	54	28	6.9	3.7	110		
Climbing perch *(Anabas testudines)*	16-19 cm	—	6	81	—	14	80	—	—	—	—		
Singhi	20-23 cm	—	6	110	—	15	73	—	—	—	—	Whole fish	data resulted from the CRP
Magur	18-21 cm	174	9	104	26	19	65	27	7.2	4.8	118		
Climbing perch	14-17 cm	—	9	88	—	13	78	—	—	—	—		
Singhi	≥20 cm	—	16	160	—	3	7	—	—	—	—	Flesh	data resulted from the CRP
Magur	"	174	19	182	26	4	8	27	7.2	4.8	118		
Climbing perch	"	—	16	119	—	4	7	—	—	—	—		
Silver perch *(Bidyanus bidyanus)*	18-25 cm	440	13	19	5	0.7	5	25	2.0	20	92	Flesh	data resulted from the CRP
Expected TF (range) from temperate data (TRS 364)			2000 (30–3000)			60 (1–1000)							IAEA 364 [III-4]

[a] Adapted from Ref. [III-3].
[b] SL: Standard length (snout to hypural plate).
[c] Modelled accounting for dissolved K^+ and suspended solids.
[d] Modelled accounting for dissolved Ca^{2+}.
[e] 20 g fish (juveniles) were excluded for failing normality and heteroscedasticity tests.
[f] —: data not available.

TABLE III-3. TRANSFER FACTORS FROM FRESHWATER TO VARIOUS ANIMALS COLLECTED FOR THE CRP AND GIVEN IN IAEA TRS 364 [III-4]

Radionuclide	Animal	Geometric mean of values observed	Number of observations	IAEA TRS 364 values		
				Low	Expected	High
Pb-210	Fish	24	15	100	300	300
	Mollusc	3 700	5	—[a]	—	—
	Reptiles	19	3	—	—	—
Po-210	Shrimp	120	2	—	—	—
	Fish	3 900	57	10	50	500
	Mollusc	13 000	1	—	—	—
	Reptiles	300	4	—	—	—
Ra-226	Shrimp	70	1	—	—	—
	Fish	66	64	10	50	200
	Mollusc	350	61	—	—	—
	Reptiles	12	7	—	—	—
U-238	Fish	3.5	49	2	10	50
	Mollusc	50	1	—	—	—
	Reptiles	3.8	5	—	—	—

[a] —: data not available.

REFERENCES FOR ANNEX III

[III-1] SRIVASTAVA, A., DENSCHALAG, H.O., KELBER, O., URICH, K., Accumulation and discharge behaviour of Cs-137 by zebra fish (Brachydanio rerio) in different aquatic environments, J. Radioanal. Nucl. Chem. **138** (1990) 165.

[III-2] SRIVASTAVA, A., REDDY, S.J., URICH, K., DENSCHALAG, H.O., Uptake and release kinetics of ^{134}Cs by goldfish (Carassius auratus) and ^{137}Cs by zebra fish (Brachydanio rerio) in controlled aquatic environment, J. Radioanal. Nucl. Chem. **182** (1994) 6.

[III-3] TWINING, J.R., MARKICH, S.J., FERRIS, J.M., Determinants of radiological dose from Sr and Cs accumulated by tropical freshwater fish, Proc. Pacific Basin Nuclear Conference, Banff, Canada (1998).

[III-4] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Reports Series No. 364, IAEA, Vienna (1994).

ANNEX IV.

TRANSFER FACTORS OF RADIONUCLIDES ^{137}CS, ^{90}SR AND ^{65}ZN FROM SOIL TO PLANTS IN INDIA

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IV-1. INTRODUCTION

Nuclear power is a major source of electricity in more than thirty countries. In India there are ten operating nuclear reactors producing about 1700 MW of electricity every year. After the accident at Chernobyl on 26 April 1986, worldwide interest grew to evaluate radiation doses that may be received by humans from exposure to radionuclides released by nuclear facilities to the environment and to assess the long-term effects on human health that these radionuclides can cause.

In general, assessments of the radiological impact of radionuclides discharged to the environment make use of environmental models. In these models the amount of radionuclides transferred from soil to plant is calculated with a TF, which is the ratio of activity concentration in plant edible parts to that in soil. The IAEA Technical Report Series (TRS) No. 364 "Handbook of Parameter Values for Prediction of Radionuclide Transfer in the Ecosystems" [IV-1] provides numerical values for these TF which are based entirely on data for crops, animals and conditions in temperate climate zones. Very few data were available on the transfer and uptake of radionuclides in tropical and subtropical ecosystems. The determination of TF from soil to plants is of primary importance in evaluating internal doses by ingestion because most of the food consumed in India originates from terrestrial sources.

When modelling the transfer of radionuclides from soil to plant, it is important to understand the processes that influence the accumulation and mobility of radionuclides in soils as these directly influence their absorption by plants. It is essential to understand the behavior of the soil constituents and of the mobilizing agents in relation to these radionuclides to develop techniques for treating contaminated soils to minimize their transfer to the food chain. Adsorption processes, for example, can reduce or delay the availability to plants of any radionuclide added to the soil. Both soil clays and organic matter can bind to ionic caesium. The clay mineral illite is a more effective sorbent than montmorillonite, kaolinite or vermiculite [IV-2].

The adsorption of zinc by the soil can be influenced by the pH of soil since studies have shown that zinc is more available to plants under acid soil conditions than under alkaline soil conditions. In laboratory experiments with clays and organic matter, it has been determined that more zinc is absorbed in basic than in acidic media [IV-3]. In both terrestrial and aquatic ecosystems, strong binding of ^{137}Cs to soils and sediments reduces its mobility and consequently its assimilation by biota. In general, caesium is not a very mobile element in the soil system, but certain soil conditions can enhance its mobility and biological availability. Caesium behaves similarly to potassium and is easily absorbed from solution by plant roots, fungi and other living systems and is efficiently absorbed in the digestive system of mammals.

A study is described here that assessed the transfer of ^{137}Cs, ^{90}Sr and ^{65}Zn from soil to pearl millet and sorghum in natural rain fed conditions in the field and under irrigated conditions in pot culture.

IV-2. MATERIALS AND METHODS

IV-2.1. Pot experiment

A greenhouse experiment was conducted using three radionuclides, namely ^{137}Cs, ^{90}Sr and ^{65}Zn. Glazed pots of 30 cm in height and 20 cm in diameter were filled with 8 kg of soil collected from the Indian Agricultural Research Institute (IARI) Farm, New Delhi, India. Soil used in pot experiments was prepared with two different activity concentrations for each radionuclide: 148 kBq/kg and 296 kBq/kg dry mass (DM).

To label the soil with radionuclides, a premix of the soil was prepared by adding the required amount of each radionuclide (^{137}Cs, ^{90}Sr and ^{65}Zn) as 10 ml solution to 500 g of the air-dried soil. This premix was brought to 50% of water saturation and mixed thoroughly; it was then air-dried, ground and mixed uniformly with the remaining quantity of the processed soil from each pot. The labelled soil was placed in the respective pots and water was added to bring the soil moisture content to 50% of the water saturation value.

The pots containing the treated soil were left for equilibration of the radionuclides with soil by subjecting them to drying and wetting cycles for ten weeks. Every week the soil in the pots was mixed and water was added in sufficient amount to saturate the soil to about 50%. After equilibration was attained, three composite core samples of soil from each pot were collected to check the homogeneity of the radionuclide distribution. Crops of pearl millet (*Pennisetum typhoides*), variety M-179, and sorghum (*Sorghum vulgare*), variety PC-121, were sown, and the recommended doses of N, P_2O_5 and K_2O were applied (80, 40, 40 kg/ha respectively) to each pot. The plants were grown under irrigated conditions. The experiment was replicated three times during the three growing seasons of 1994, 1995 and 1996.

The crops were harvested at maturity and the plants were cut at 2 cm above the soil level. The plants were separated into two components of grain and straw after recording their dry matter yield. The plant samples were ground in a stainless-steel mill taking care to avoid cross contamination of samples. The whole grain and ground straw samples were used for measurements of ^{137}Cs and ^{65}Zn directly using a 2.5" × 2.5" NaI(Tl) well type detector installed in a lead shield of 15 cm in thickness. Analysis of ^{90}Sr was carried out by digesting the samples with acid mixture of ($HClO_4$ and HNO_3 in the ratio of 1 to 1). Sr-90 and ^{90}Y were separated radiochemically with the procedure outlined in the IAEA Technical Report No. 295 [IV-4] and counted using a Geiger-Müller counter.

Similarly, soil samples to a depth of 20 cm were taken from each pot and allowed to air-dry, processed and ground to 100 mesh in a porcelain pestle mortar. Measurements of activity of ^{137}Cs, ^{65}Zn and ^{90}Sr were made using the same methods as for plant samples.

IV-2.2. Field Experiment

A similar experiment was conducted for ^{137}Cs and ^{90}Sr under field conditions in the Gamma Garden of the IARI Research Farm during the 1994 and 1995 Kharif monsoon seasons. Soil in microplots 1 m × 1 m (1 m^2) in size situated in bigger yield plots of 3 m × 3 m (9m^2) was labelled with ^{137}Cs and ^{90}Sr to an activity concentration of 74 kBq/kg DM and 148 kBq/kg DM. The entire upper 5 cm soil of the microplots (75–80 kg) was dug out and sprayed with a 500 ml solution of radionuclide containing the required amount of activity. The radionuclides were mixed thoroughly with the entire soil. The soil was then transferred back to the microplots and brought to 50% water saturation level to a depth of 20 cm. Radionuclides were allowed to equilibrate in soil for eight weeks. During this period, the soil was kept at between 35 and 50% of its moisture saturation level.

TABLE IV-1. CHARACTERISTICS OF SOIL OF EXPERIMENTAL SITE

Parameter		Range or Value
pH (H_2O)		7.7 to 7.9
pH ($CaCl_2$)		7.0 to 7.2
Organic matter (%)		1.75 to 1.85
CEC (cmol/kg soil)		8.30
Exchangeable K (me/100 g soil)		0.30 to 0.36
Exchangeable Ca (me/100 g soil)		6.20 to 6.52
Sand (%)		81.2
Silt (%)		8.6
Clay (%)		10.2
Clay type	Illite	+++ [a]
	Kaolinite	++
	Chlorite	+
	Quartz	+
Texture		Sandy/loam

[a] '+': indicates relative abundance of clay type.

After equilibration, crops of pearl millet, variety M-179, and sorghum, variety PC-121, were grown with a row to row spacing of 40 cm. Crops were then fertilized with N (80 kg/ha) by urea applied in two splits, P_2O_5 (40 kg/ha) by single superphosphate and K_2O (40 kg/ha) by potassium chloride.

At maturity, the plants were harvested and separated into grain and straw. Activity in the samples collected from the field was then measured in a similar way as was done in case of the greenhouse experiment. The characteristics of the soil used in greenhouse and field experiments are given in Table IV-1.

During the 1996 monsoon season the field experiment was conducted at a new site where the soil was treated with much lower activity concentrations of ^{137}Cs and ^{90}Sr (18.5 and 37.0 kBq/kg). The crops grown were pearl millet, sorghum, soybean and cowpea. The plants were harvested at maturity and the activity of ^{137}Cs and ^{90}Sr was determined in the same way as described above.

IV-3. RESULTS AND DISCUSSION

IV-3.1. Soil to plant transfer factors of ^{137}Cs, ^{90}Sr and ^{65}Zn

Soil to plant TF were determined using the following definition:

$$\mathrm{TF} = \frac{\text{Activity concentration in crop } (\frac{Bq}{kg}, \text{DM})}{\text{Activity concentration in soil } (\frac{Bq}{kg}, \text{DM})} \qquad \text{(IV-1)}$$

Data presented in Tables IV-2 and IV-3 are those determined under pot culture conditions in 1994, 1995 and 1996 and under field conditions in 1994 and 1995. Results of the 1996 experiment with pearl millet, sorghum, soybean and cowpea for ^{137}Cs and ^{90}Sr are given in Table IV-4.

Caesium-137

The data for ^{137}Cs revealed that in the first year after contamination (1994) under greenhouse conditions at 148 kBq/kg (DM) in soil the TF in pearl millet grain and straw were 0.006 and 0.012, respectively. At the higher activity concentration of 296 kBq/kg (DM) the TF were much lower: 0.004 4 in pearl millet grain and 0.006 4 in straw respectively.

In the case of sorghum, the TF were similar in grain at both the levels of contamination and ranged from 0.004 5 at the lower level of contamination of soil to 0.004 7 at the higher level of contamination of soil, although in one replication the TF determined was 0.008; this may be due to uneven growth of roots in soil. In sorghum straw, the TF ranged from 0.012 5 at the lower level of contamination and 0.007 7 at the higher level of contamination, although in one replication where a higher value was determined (0.011 5).

In case of grains for both pearl millet and sorghum, the absolute uptake of ^{137}Cs (Bq/kg grain) almost doubled when the soil contamination level was doubled but such trend was not observed for straw [IV-5].

In the second year of the experiment (1995), TF decreased considerably in pearl millet, and sorghum grain and straw compared with those observed in 1994, by up to a factor of five. In 1996, the TF decreased further, but the decrease was much smaller compared with that in the second year. The trend in reduction of the TF was similar for both activity concentrations in soil.

Under field conditions, the TF for ^{137}Cs in pearl millet ranged from 0.004 5 in grain to 0.008 5 in straw at the higher activity concentration of soil in the first year after contamination. At the lower activity concentration, the values were lower (0.002 2 for grains and 0.003 3 for straw).

In sorghum, the TF for ^{137}Cs were similar for grain and straw at the higher activity concentration (0.006 1 and 0.006 9 respectively), but at the lower activity concentration the TF for ^{137}Cs in sorghum grain (0.002 0) were much lower than in straw (0.004 1).

However, the ^{137}Cs activity concentration in both pearl millet and sorghum grain as well as straw was nearly four times higher for the higher activity concentration in soil compared with that at the lower level.

In the second year after treatment, the TF of ^{137}Cs decreased much more than those determined under pot culture conditions. The TF determined in 1995 were 6 to 20 times lower than those observed in the previous year. In sorghum, the decrease was more in the straw than in grains.

In the third year of experiment with fresh treatment of soil with ^{137}Cs – although at much lower activity concentration – under irrigated conditions the TF for both pearl millet and sorghum were two to three times higher than those observed in 1994 under rain fed conditions for a soil contamination of 74 kBq/kg DM (see Table IV-3).

The TF of ^{137}Cs reported by Gerzabek et al. [IV-6] for wheat straw from two field studies at two sites contaminated by Chernobyl fallout were much higher than those observed for pearl millet and sorghum in the present study. Glabiszewski et al. [IV-7] reported that plant contents of ^{90}Sr and ^{65}Zn declined with increasing growth period in different crops; the contents of ^{137}Cs showed no consistent trends but were generally highest in peas and lowest in maize.

Tulin et al. [IV-8] found that the increasing levels of potassium fertilization reduce the absorption of ^{137}Cs by oats from soil contaminated from the Chernobyl accident; similar observations were reported by Orlovius and Sattler [IV-9]. Although in the present investigation, the soil was fertilized with 40 kg/ha of K_2O and contained the potassium rich illite as the dominating clay mineral, no decrease in the soil to plant TF of ^{137}Cs was observed with an increase of the activity concentrations in soil.

TABLE IV-2. TRANSFER FACTORS OF CS-137, SR-90 AND ZN-65 IN PEARL MILLET AND SORGHUM UNDER POT CULTURE CONDITIONS

Year	Activity concentration in soil (kBq/kg DM)	Transfer Factor ± Standard Deviation			
		Pearl millet		Sorghum	
		Grain	Straw	Grain	Straw
		Cs-137			
1994	148	0.006 0 ± 0.001	0.011 8 ± 0.001 8	0.004 5 ± 0.000 1	0.012 5 ± 0.000 3
	296	0.004 5 ± 0.000 4	0.006 4 ± 0.000 2	0.004 7 ± 0.000 3	0.007 7 ± 0.000 1
1995	148	0.001 1 ± 0.000 2	0.002 2 ± 0.000 3	0.001 3 ± 0.000 1	0.002 2 ± 0.000 1
	296	0.002 6 ± 0.000 2	0.003 3 ± 0.000 2	0.002 6 ± 0.000 1	0.003 7 ± 0.000 2
1996	148	0.000 94 ± 0.000 1	0.001 4 ± 0.000 1	0.001 3 ± 0.000 1	0.001 8 ± 0.000 3
	296	0.001 9 ± 0.000 1	0.002 8 ± 0.000 3	0.001 9 ± 0.000 1	0.003 3 ± 0.000 2
		Sr-90			
1994	148	0.070 ± 0.01	0.13 ± 0.03	0.085 ± 0.01	0.16 ± 0.01
	296	0.15 ± 0.03	0.15 ± 0.02	0.13 ± 0.01	0.14 ± 0.01
1995	148	0.019 ± 0.001	0.035 ± 0.001	0.023 ± 0.001	0.039 ± 0.002
	296	0.024 ± 0.001	0.044 ± 0.002	0.023 ± 0.001	0.037 ± 0.001
1996	148	0.014 ± 0.002	0.028 ± 0.002	0.019 ± 0.031	0.031 ± 0.001
	296	0.019 ± 0.002	0.036 ± 0.003	0.016 ± 0.001	0.029 ± 0.001
		Zn-65			
1994	148	0.70 ± 0.13	0.39 ± 0.05	0.43 ± 0.01	0.57 ± 0.01
	296	0.33 ± 0.04	0.30 ± 0.03	0.40 ± 0.01	0.51 ± 0.03
1995	148	0.21 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	0.17 ± 0.01
	296	0.16 ± 0.01	0.095 ± 0.01	0.11 ± 0.01	0.13 ± 0.01
1996	148	0.18 ± 0.01	0.11 ± 0.01	0.18 ± 0.02	0.29 ± 0.03
	296	0.19 ± 0.01	0.11 ± 0.01	0.12 ± 0.01	0.14 ± 0.01

TABLE IV-3. TRANSFER FACTORS OF CS-137 AND SR-90 IN PEARL MILLET AND SORGHUM UNDER FIELD CONDITIONS

Year	Activity concentration in soil (kBq/kg DM)	Transfer Factor ± Standard Deviation			
		Pearl millet		Sorghum	
		Grain	Straw	Grain	Straw
		Cs-137			
1994	74	0.002 2 ± 0.000 4	0.003 3 ± 0.000 4	0.002 0 ± 0.000 7	0.004 1 ± 0.000 6
	148	0.004 5 ± 0.000 1	0.008 5 ± 0.000 7	0.006 1 ± 0.000 2	0.006 9 ± 0.000 1
1995	74	0.000 28 ± 0.000 1	0.000 42 ± 0.000 1	0.000 15 ± 0.000 1	0.000 65 ± 0.000 1
	148	0.000 49 ± 0.000 1	0.000 67 ± 0.000 2	0.000 31 ± 0.000 1	0.000 53 ± 0.000 1
		Sr-90			
1994	74	0.39 ± 0.01	0.78 ± 0.01	0.53 ± 0.01	1.23 ± 0.18
	148	0.63 ± 0.04	0.75 ± 0.06	0.89 ± 0.06	1.01 ± 0.04
1995	74	0.22 ± 0.04	0.38 ± 0.01	0.30 ± 0.04	0.42 ± 0.01
	148	0.31 ± 0.01	0.68 ± 0.05	0.59 ± 0.04	0.61 ± 0.05

TABLE IV-4. TRANSFER FACTORS OF CS-137 AND SR-90 IN PEARL MILLET, SORGHUM, SOYBEAN AND COWPEA UNDER FIELD CONDITIONS IN 1996

Activity concentration in soil (kBq/kg DM)	Transfer Factor ± Standard Deviation			
	Pearl millet		Sorghum	
	Grain	Straw	Grain	Straw
		Cs-137		
18.5	0.006 1 ± 0.000 2	0.008 1 ± 0.000 2	0.006 7 ± 0.000 4	0.008 7 ± 0.000 6
37	0.008 6 ± 0.000 3	0.009 6 ± 0.000 5	0.007 7 ± 0.000 1	0.009 1 ± 0.000 4
		Sr-90		
18.5	5.3 ± 1.0	9.4 ± 0.3	6.0 ± 1.2	9.5 ± 0.3
37	6.8 ± 0.5	9.7 ± 0.3	5.8 ± 0.2	9.6 ± 0.2
	Soybean		Cowpea	
	Grain	Straw	Grain	Straw
		Cs-137		
18.5	0.004 1 ± 0.000 6	0.009 6 ± 0.000 7	0.002 7 ± 0.000 3	0.005 4 ± 0.000 4
37	0.004 0 ± 0.000 3	0.008 4 ± 0.000 6	0.003 6 ± 0.000 1	0.006 4 ± 0.000 2
		Sr-90		
18.5	8.2 ± 0.4	9.5 ± 0.3	3.4 ± 0.7	6.0 ± 0.4
37	7.8 ± 0.3	8.9 ± 0.2	2.4 ± 0.3	6.1 ± 0.1

Strontium-90

At the activity concentration of 148 kBq/kg DM in soil, the TF of ^{90}Sr in pearl millet grain and straw ranged from 0.070 and 0.13, respectively, in the first year after contamination under pot culture conditions. At the higher activity concentration of 296 kBq/kg DM, the TF were much higher and were 0.15 for both pearl millet grain and straw portion.

In the case of sorghum grain, the TF were found to be 0.085 at the lower activity concentration in soil and 0.13 at the higher level. In sorghum straw, the TF were 0.16 at the lower level of activity concentration and 0.14 at the higher level.

The data showed that in both the crops and also in grain and straw, the absolute uptake of ^{90}Sr (Bq/kg DM grain) was nearly three times more at the higher level of activity concentration in soil than observed at the lower level. The probable reason for this higher uptake may be that at the higher level the availability of ^{90}Sr in soil solution increases and consequently more of it is absorbed by plant roots [IV-10].

Similar to ^{137}Cs, the TF for ^{90}Sr also decreased by about five times in the second-year crops. But in the third year the soil to plant TF in both pearl millet and sorghum grain as well as straw parts declined marginally.

Under field conditions, at the higher activity concentration of 148 kBq/kg DM the TF of ^{90}Sr in pearl millet ranged from 0.63 in grain to 0.75 in straw in the first year after labelling. At the lower activity concentration in soil of 74 kBq/kg DM the TF in grain was much lower (0.39) while in straw the TF was similar (0.78). In sorghum the mean TF values at 148 kBq/kg DM were 0.89 for grain and 1.04 for straw. However, at 74 kBq/kg DM the TF in sorghum grain (0.53) were much lower than in straw (1.23).

Uptake of ^{90}Sr by pearl millet and sorghum was nearly 50 to 100 times higher than that of ^{137}Cs under identical conditions of crop growth and soil contamination. Kiepul et al. [IV-11] also found that activity concentrations of ^{90}Sr in peas were higher than ^{137}Cs. Hrynczuk and Sienkiewicz [IV-12] reported that potatoes and maize absorbed similar amounts of ^{137}Cs and

^{90}Sr from soil to which straw containing the two radionuclides was applied as from that treated with manure.

The decrease in TF of ^{90}Sr under field conditions for both pearl millet and sorghum was much lower than for those observed under pot culture conditions, and under field conditions for ^{137}Cs. The latter two decreased by a factor of only two to three.

Zinc-65

The TF of ^{65}Zn were only determined for the pot experiment and were nearly 40 times higher than those of ^{137}Cs.

In the case of pearl millet grain, the TF ranged from 0.70 at the lower activity concentration in soil (148 kBq/kg DM) to 0.33 at the higher soil activity concentration (296 kBq/kg DM). The TF of ^{65}Zn were lower in pearl millet straw ranging from 0.39 at the lower activity concentration to 0.30 at the higher activity concentration.

The TF for sorghum were lower than for pearl millet. Also, there was not much effect of the soil activity concentration with ^{65}Zn on its TF. In sorghum TF were 0.43 and 0.57 for grain and straw respectively.

The probable reason for the higher TF of ^{65}Zn observed is that zinc is absorbed by plant roots in large amounts since it is an essential plant nutrient and translocated to above ground parts of plants.

From these studies we concluded that at higher level of soil contamination, TF of ^{137}Cs, ^{90}Sr and ^{65}Zn are usually a factor up to 2 higher. Also, the TF are much higher in the first year in the crop taken immediately after contamination and decreased considerably in the second- and third-year crops.

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ANNEX V.

ABSORPTION AND ACCUMULATION OF 85SR BY RICE PLANTS AND SOIL-TO-PLANT TRANSFER FACTORS IN KOREA

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V-1. INTRODUCTION

The use of nuclear energy, which rapidly increased in Korea during the last few decades, inevitably entails the release of radionuclides into the environment. Released radionuclides can become sources of internal radiation for the human body after their intake by man through ingestion of food [V-1–V-3]. Accordingly, it is necessary to understand the transport behavior of radionuclides in the agricultural ecosystem to assess the environmental impact of the nuclear facilities and for preparedness for agricultural countermeasures in case of nuclear accidents leading to the contamination of farmland with radionuclides.

Radionuclides such as ^{90}Sr and ^{137}Cs remain available in the rooting zone when released to soil [V-4–V-8]. Numerous studies on the TF from soil to plant have been carried out by means of radiotracer techniques [V-1–V-3, V-9, V-10]; few publications on the uptake of ^{85}Sr by rice, however, are available. Therefore, pot experiments were carried out with different activity concentrations of ^{85}Sr to investigate the transfer from soil to plant for two rice cultivars and to study the effect of ^{85}Sr in soil on the growth and yield of rice plants. Sr-85 was used instead of ^{90}Sr because of its shorter half-life and because ^{85}Sr is easier to determine analytically.

V-2. MATERIAL AND METHODS

Plants of the rice cultivars used for this experiment (Ilpoombyeo, a late maturing variety and Odaebyeo, an early maturing variety) were grown on a/2000 plastic pots containing 13 kg of an air-dried sandy loam soil. Carrier free ^{85}Sr ($SrCl_2$) was used to label the soil at three levels: 0 (control), 74 Bq/kg and 222 Bq/kg dry mass (DM). Sr-85 was applied to the soil surface 20 days before transplanting the rice. During the equilibration period the pots received no water to let ^{85}Sr diffuse through the whole soil. Fertilisers were applied as urea (1.8 g/pot), fused phosphate (5.3 g/pot) and potassium chloride (2.0 g/pot). The physico-chemical properties of the soil used are given in Table V-1.

The pots with rice plants were placed in a vinyl greenhouse, built in Suwon, according to a randomized design with 3 replications. The pots were irrigated so that a layer of 3 cm of water was formed immediately after the placement. Two hills (three plants/hill) of rice seedlings were transplanted to the pots on 7 June 1996. Appropriate amounts of water were supplied almost every day and the pots were not drained until the yellow-ripening stage. Additional urea was added on 21 June 1996 (1.1 g/pot) and on 31 July 1996 (0.7 g/pot). On 31 July 1996 0.6 g of potassium chloride was also added to each pot.

Plants of Odaebyeo and Ilpoombyeo were harvested on 2 and 31 October 1996. Plant samples were divided into straw and grain, which was further subdivided into brown rice and husk after it was air-dried. Plant samples were dried at 80°C for 48 hours and their DM measured. Thereafter, samples were ground in a mill with a 40-mesh sieve. Samples of about 500 g of soil per pot were taken from the top 20 cm layer after harvesting and dried at air temperature.

TABLE V-1. PHYSICO-CHEMICAL PROPERTIES OF THE DRY SOIL USED IN THE UPTAKE EXPERIMENT

pH (1:5)	Total-N (g/kg)	Average P_2O_5 (mg/kg)	Exchange cations (cmol/kg)				Soil texture
			K	Ca	Mg	Na	
6.5	0.7	72	0.27	2.73	0.48	0.36	Sandy loam

Plant samples were transferred to test tubes with a 1 cm diameter in 4 cm layers. Soil samples were transferred to test tubes in the same way after passing through a 2 mm grid sieve. Activity in the samples was measured using a gamma counter (LB 951 G, NaI detector).

Transfer factors (TF) of ^{85}Sr from soil to plant were calculated using the equation:

$$\mathrm{TF} = \frac{\text{Activity concentration of Sr}-85\text{ in each plant part}\left(\frac{\mathrm{Bq}}{\mathrm{kg}},\mathrm{DM}\right)}{\text{Activity concentration of Sr}-85\text{ in soil after harvesting}\left(\frac{\mathrm{Bq}}{\mathrm{kg}},\mathrm{DM}\right)} \quad \text{(V-1)}$$

V-3. RESULTS AND DISCUSSION

Activity concentrations of ^{85}Sr obtained during our investigations are shown in Table V-2. Activity concentrations of ^{85}Sr measured in the plants when the activity concentration in soil was 222 Bq/kg DM were 2 to 3 times higher than those observed during the experiment with an activity concentration in soil of 74 Bq/kg DM. In all cases activity concentrations in brown rice were much lower than those in straw and husk and activity concentrations in the cultivar Odaebyeo were higher than those in Ilpoombyeo. These results agree with those of Tensho and Mitsui [V-11] who reported on their pot experiment that activity concentrations of ^{90}Sr in the straw were much higher than those in grain.

Table V-3 shows the amounts and percentages of ^{85}Sr, which were absorbed for each pot. Uptake fractions for the rice plants of the Ilpoombyeo variety were between 0.39% and 0.43%, while the fraction absorbed by plants of the Odaebyeo variety were about 1.5 times higher, between 0.66 and 0.73%. This means that uptake of ^{85}Sr depends strongly on the rice variety. Uptake fractions of ^{85}Sr were independent of the activity concentrations of ^{85}Sr in soil. Almost all of the ^{85}Sr absorbed by the plants accumulated in straw (90.2% on average) and husk (8.5% on average), while the fraction of ^{85}Sr in brown rice was about 1.3% on average.

Under field conditions the uptake will depend strongly on the planting density, the growth rate of the plant and the distribution of ^{85}Sr in soil. Yamata et al. [V-12] reported that the ^{90}Sr uptake of rice ranged from 0.42% to 1.66% for Japanese field condition.

Table V-4 shows the TF obtained in the experiment. Values range from 0.037 for brown rice to 4.1 for straw. In decreasing order TF were highest for the straw portion of the plant, followed by those for husk; TF for brown rice were the lowest. Tsumura et al. [V-13] reported TF of ^{90}Sr for brown rice between 0.016 and 0.025 for their pot experiment. These values are lower than those determined our experiment; the difference may be caused by the fact that Tsumara et al. [V-13] used a clay-loam soil with a higher clay content and higher cation exchange capacity (14 meq/100g), as well as a higher application of lime (5-30 g/3 kg soil) or compost (100-300 g/3 kg soil). According to Ng et al. [V-10] soil-to-plant TF of ^{90}Sr range from 0.05 to 17.5 on a DM basis for different combinations of crops and soils. It is, therefore, necessary to investigate TF for various types of crops and soils, since small differences may significantly affect the assessment of doses received by members of the public because of the high consumption rate of rice in Korea.

TABLE V-2. ACTIVITY CONCENTRATIONS OF SR-85 IN RICE

Rice cultivars	Activity concentration of Sr-85 in soil (Bq/kg DM)	Activity concentration of Sr-85 in rice plants (kcpm/kg, DM) ± Standard Deviation		
		Straw	Husk	Brown rice
Ilpoombyeo	74	180 ± 60	50 ± 17	2.1 ± 1.4
	222	464 ± 33	126 ± 8	6.3 ± 1.5
Odaebyeo	74	272 ± 29	108 ± 13	3.1 ± 1.7
	222	620 ± 118	355 ± 12	10.2 ± 2.8

TABLE V-3. UPTAKE OF SR-85 PER POT, EXPRESSED AS AMOUNTS AND AS PERCENTAGES

Rice cultivars	Activity concentration of Sr-85 in soil (Bq/kg DM)	Activity concentration of Sr-85 in rice plant (kcpm/pot) ± Standard Deviation			Sr-85 uptake fraction (%) [a]
		Straw	Husk	Brown rice	
Ilpoombyeo	74	12.2 ± 1.9 (91.2) [b]	1.00 ± 0.15 (7.5)	0.17 ± 0.07 (1.3)	0.39 ± 0.6
	222	39.1 ± 4.2 (92.6)	2.59 ± 0.26 (6.1)	0.53 ± 0.12 (1.3)	0.43 ± 0.04
Odaebyeo	74	21.5 ± 4.7 (90.3)	2.05 ± 0.34 (8.6)	0.25 ± 0.12 (1.1)	0.73 ± 0.14
	222	55.7 ± 15.5 (86.8)	7.55 ± 1.27 (11.8)	0.89 ± 0.15 (1.4)	0.66 ± 0.17

[a] Sr-85 uptake fraction (%) was determined as following: $\frac{\text{Total Sr-85 activity (Bq) in a plant}}{\text{Total Sr-85 activity (Bq) added to a pot}}$.

[b] Values in parentheses indicate the percentages of absorbed Sr-85 present in the pertaining part of the plant.

TABLE V-4. TRANSFER FACTORS OF SR-85

Rice cultivars	Activity concentration of Sr-85 in soil (Bq/kg DM)	Transfer Factor ± Standard Deviation		
		Straw	Husk	Brown rice
Ilpoombyeo	74	3.8 ± 1.7	1.1 ± 0.5	0.046 ± 0.035
	222	2.7 ± 0.3	0.75 ± 0.1	0.037 ± 0.007
Odaebyeo	74	4.1 ± 0.4	1.6 ± 0.2	0.048 ± 0.025
	222	3.7 ± 0.9	2.1 ± 0.3	0.060 ± 0.018

TABLE V-5. DRY MASS (DM) OF RICE PLANTS

Rice cultivars	Activity concentration of Sr-85 in soil (Bq/kg DM)	Weight of rice plants (g DM/pot) ± Standard Deviation		
		Straw	Husk	Brown rice
Ilpoombyeo	0	80 ± 6	21.1 ± 2.8	85.2 ± 11.5
	74	71 ± 12	20.5 ± 2.6	83.1 ± 10.5
	222	84 ± 4	20.4 ± 1.4	82.8 ± 5.4
Odaebyeo	0	80 ± 12	16.4 ± 3.2	69.4 ± 13.6
	74	83 ± 3	18.9 ± 1.7	79.9 ± 7.1
	222	90 ± 11	21.1 ± 3.0	89.5 ± 12.7

Although we did not notice an influence of the ^{85}Sr activity concentration in soil, Choi et al. [V-14] reported for their pot experiment that ^{90}Sr TF for brown rice differed significantly when soil was treated with 5.2 Bq/g in comparison with 31.2 Bq/g.

Dry weight values of the rice plants are reported in Table V-5; there were no significant differences between control and treated groups observed in any case studied. This result indicates that ^{85}Sr uptake had no effect on the growth of rice and agrees with reports by Kim and Choi et al. [V-5, V-14] that ^{90}Sr applied to soil had no effect on the growth and yield of rice.

V-4. CONCLUSIONS

Radiostrontium taken up in a pot experiment from soil by rice plant amounted to only 1.3% in the total crop. Almost all radiostrontium absorbed by the plants was accumulated in the straw and husk parts of the plants. This is because strontium, like calcium, is not readily translocated in plants and remains in plant tissue after transpiration.

The TF of ^{85}Sr from soil to brown rice, the edible part of rice plants, ranged from 0.037 to 0.060. Because TFs depend on the variety, clay content and cation exchange capacity of soil and the application of lime and compost, further investigations are necessary.

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ANNEX VI.

TRANSFER FACTORS OF RADIONUCLIDES FROM SOIL TO CROPS IN TAIWAN, CHINA

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VI-1. OBJECTIVES

Although the environmental levels of ^{137}Cs and ^{90}Sr are normally low [VI-1], owing to their long half-lives (30 y and 28.8 y) and high affinity to muscle and bone tissues respectively [VI-2], they are important radionuclides in radioecological studies. To assess the radiation doses received by individuals from these radionuclides it is necessary to study their transfer to agricultural crops [VI-3]. Because of the high consumption of rice in Taiwan, China and other east-Asian countries, attention was mainly given to rice. The Taiwan Radiation Monitoring Center, Atomic Energy Council, Executive Yuan, Taiwan, China (TRMC) started its first study on the transfer of the radionuclides from paddy soil to crops in 1981 [VI-4].

The aim of the IAEA's Coordinated Research Project "Transfer of Radionuclides from Air, Soil and Freshwater to the Food chain of Man in Tropical and Subtropical Environments", sponsored by the International Union of Radioecologists (IUR), is to determine a set of key transfer parameter values for some radionuclides from soil to edible parts of plants, from freshwater to fish, from air to plants, and from plants to animals, typical of the tropical and subtropical ecosystems. Such parameters can be used in dose assessment models for setting release limits of radioactive effluents from nuclear facilities [VI-5]. With the same aim, TRMC also began tracer experiments to determine sets of the TF of radionuclides from soil to various crops, which can be applied in dose assessments in Taiwan, China.

In spring 1994, TRMC began to cultivate rice plants in pots in the TRMC's greenhouse with ^{137}Cs and ^{85}Sr sources. For comparison, a field study was performed at the same time at Taiwan Provincial Kaohsiung Agricultural Improvement Station. Two of the most popular leafy vegetables in Taiwan, China (Chinese mustard and water convolvulus) were also studied in the TRMC's greenhouse. Another three common vegetables in Taiwan, China, i.e. cabbage, brassica chinensis and sweet potato, were studied by field experiments.

VI-2. EXPERIMENTAL DESIGN

Two typical paddy soils were chosen for the cultivation of rice: $soil_{PT}$, collected from the Taiwan Provincial Kaohsiung Agricultural Improvement Station, and $soil_{LT}$, taken from northern Taiwan, China, and which contained ^{137}Cs from nuclear weapons fallout. Samples of about 30 kg of $soil_{PT}$ were thoroughly mixed with tracers of ^{137}Cs and ^{85}Sr, and then transferred to two Wagner pots, weighing 13.5 kg each. Two pots were prepared with $soil_{PT}$ to which tracers had been added, two pots with $soil_{LT}$ and another four pots with $soil_{PT}$ without tracer, as blank.

The pots were placed in a greenhouse and were irrigated with water. Three to five rice plant seedlings (Tainung 67, *Oryza sativa*) were planted in each pot, about 3 weeks after germination. The day-night cycle in the greenhouse was similar to the one in the field study in Pington, where the Taiwan Provincial Kaohsiung Agricultural Improvement Station is located, except for slightly higher temperature and moisture conditions. The sowing schedule and application of chemical fertilizer and pesticides followed the actual farming practices of the area. The procedures to cultivate the vegetables using $soil_{LT}$ are similar to those used for rice, except that their growing period is shorter.

At harvest, both samples of the edible parts of the crops, i.e. rice grain, leaves or roots, and of soil from different depths were taken from each pot and field. The plant samples were dried and ashed, and the soil samples were dried in an oven at 100° C, because all TF are based on dry mass (DM). The activity concentrations of ^{137}Cs and ^{85}Sr were measured with a gamma-ray spectrometry system based on an HPGe detector (FWHM: 1.82 keV at 1.33 MeV) coupled to a computerized data acquisition system (4096 channel pulse height analyzer). Samples were measured in a cylindrical plastic container, which was placed directly on the detector, using a counting time of 80000 s. Efficiency calibration was carried out using a multi-gamma source mixed with agar and decay corrections were made at the beginning of the experiment.

VI-3. RESULTS

As shown in Table VI-1, there are two growing seasons in southern and central Taiwan, China, but only one growing season in northern Taiwan, China. Since TRMC is located in Kaohsiung, southern Taiwan, China, we cultivated the rice plants two times every year. All samples of soil were analysed to determine soil parameters [VI-6–VI-7], such as pH, texture, organic matters, and cation exchange capacity, because TF are dependent on these parameters; the results are shown in Table VI-2. $Soil_{PT}$ was classified as Aeric Haplaquept, fine-silty, mixed, nonacid, hyperthermic [IV-8].

The results of the pot experiment with ^{137}Cs and ^{85}Sr with $soil_{PT}$ in the TRMC's greenhouse for rough and brown rice are given in Table VI-3. Rough rice includes the hull; brown rice excludes the hull but is not polished. Lacking experience in cultivating crops, we failed in the first experiment to collect sufficient quantities of grains of rice. In the following three growing seasons, owing to the help provided by agricultural experts and farmers, we succeeded in collecting sufficient amounts of rice for analysis. The TF from $soil_{PT}$ to rough rice determined in the experiment were in the range 0.0008 to 0.016 and 0.14 to 0.24 for ^{137}Cs and ^{85}Sr, respectively. The TF from $soil_{PT}$ to brown rice were 0.0008 to 0.014 and 0.053 to 0.066 for ^{137}Cs and ^{85}Sr, respectively.

The results of the pot study using soil taken from northern Taiwan, China, $soil_{LT}$, containing ^{137}Cs from nuclear weapons fallout are shown in Table VI-4. The TF of ^{137}Cs from $soil_{LT}$ were 0.11 to rough rice, 0.008 6 to 0.013 to brown rice and 0.006 8 to polished rice, respectively. Although the properties of these two soils were quite different, the results showed that TF from $soil_{PT}$ and $soil_{LT}$, were similar, except for the last growing season for tracers-added $soil_{PT}$.

The results of the determination of TF from soil to five leafy and root vegetables are listed in Table VI-5. Data are included from both (i) the pot experiment in the greenhouse with the two kinds of leafy vegetables, Chinese cabbage and water convolvulus, and (ii) the field study of three kinds of vegetables, cabbage, *Brassica chinensis* (Bailey) and sweet potato. The TF of ^{137}Cs from $soil_{LT}$, are 0.001 1–0.089 to Chinese cabbage, 0.003 7–0.029 to water convolvulus, 0.023 to cabbage, 0.004 2 to *Brassica chinensis* (Bailey) and 0.36 to sweet potato, respectively.

VI-4. DISCUSSION AND CONCLUSIONS

The difference between the TF of ^{85}Sr and ^{137}Cs for both rough rice and polished rice may be caused by the fact that caesium is much more easily fixed than strontium in $soil_{PT}$, which contains high levels of clay [VI-9]. The higher TF of rough rice compared with those of polished rice for both ^{137}Cs and ^{85}Sr may be caused by the accumulation of these radionuclides in the bran. Most of the radionuclides are also accumulated in the hull part of the rice grain. We confirmed this by measuring the activity concentrations of the hull for both ^{137}Cs and ^{85}Sr. Table VI-3 also shows the greater TF of ^{137}Cs from $soil_{PT}$ to rough rice obtained from the field study compared to those from the pot experiment. As both of them were conducted with the same soil ($soil_{PT}$) and the same rice species (*Tainung 67*), it could have been caused by the difference of growing conditions between greenhouse and field.

TABLE VI-1. GROWING SEASON OF RICE PLANTS IN TAIWAN, CHINA

Location	Number of harvests per year	Growing periods	
		First	Second
North	1	March ~ August	n.a. [a]
Central	2	February ~ June	July ~ early December
South	2	Late January ~ June	July ~ late November

[a]n.a.: not applicable.

TABLE VI-2. PARAMETERS OF SOILS USED IN POT AND FIELD STUDY

Parameter	$Soil_{PT}$	$Soil_{LT}$
pH water	6.27	5.37
Organic matter (%)	2.74	0.49
Clay (%)	43.4	10.6
Silt (%)	50.0	8.0
Sand (%)	6.60	81.4
Texture	Silty Clay	Loamy Sand
Exchangeable K (meq/100g)	0.33	0.13
Exchangeable Ca (meq/100g)	8.69	2.32

TABLE VI-3. TRANSFER FACTORS OF CS-137 AND SR-85 $SOIL_{PT}$ TO RICE (DM BASIS) DETERMINED BY TRACER EXPERIMENTS

Experiment	Tracer	Growth period	Crop part	Transfer factor	Remark
Pot	Cs-137	January – June 1994			Fail (no harvest)
		July – November 1994	Rough rice	0.0027	
		January – June 1995	Rough rice	0.016	
			Brown rice	0.014	
		July – November 1995	Rough rice	0.0008	
			Brown rice	0.0008	
(TRMC) Greenhouse		January – June 1994			Fail (no harvest)
		July – November 1994	Rough rice	0.1	
Field	Sr-90	January – June 1995	Rough rice	0.24	
			Brown rice	0.066	
		July – November 1995	Rough rice	0.14	
			Brown rice	0.053	
	No tracer was used; source was fallout of Cs-137	January – June 1994	Rough rice	0.066	
		July – November 1994		<MDC [a]	
		January – June 1995	Rough rice	0.028	
		July – November 1995		<MDC	

[a] MDC: Minimum detectable concentration.

TABLE VI-4. TRANSFER FACTORS OF CS-137 FROM $SOIL_{LT}$ TO RICE (DM BASIS) DETERMINED BY TRACER EXPERIMENTS

Experiment	Growth period	Crop	Transfer factor
Pot	January – June 1995	Brown rice	0.008 6
		Polished rice	0.006 8
(TRMC) Greenhouse	July – November 1995	Rough rice	0.011
		Brown rice	0.013

For the second part of the investigation, i.e. the study on the vegetables, the TF were in the range 0.001 to 0.01, which were similar to those observed by Malm et al. [VI-10]. More radiocaesium was transported to leaves than to the root of leafy vegetables. On the contrary, the TF of ^{137}Cs from soil to sweet potato is much greater than to leafy vegetables.

In summary, this study confirms the low TF of caesium and strontium from soil to rice and vegetables in subtropical areas of Taiwan, China. The ranges of the dry weight TF determined during this investigation were 0.000 1 to 0.01 and 0.001 to 0.1 for ^{137}Cs and ^{85}Sr in rice, respectively, and 0.001 to 0.01 and 0.01 to 0.1 for ^{137}Cs in leafy and root vegetables, respectively.

VI-5. LITERATURE SURVEY OF TRANSFER FACTORS IN TAIWAN, CHINA

VI-5.1. Transfer factors of ^{90}Sr and ^{137}Cs from paddy soil to brown and polished rice

In a field study in 1981 [VI-4], soil and rice samples were taken from twelve cities and counties in Taiwan, China, and analysed to measure activity concentrations of ^{90}Sr and ^{137}Cs on a DM basis. The average TF of ^{90}Sr from paddy soil to brown and polished rice were 0.086 and 0.037, respectively, while the average TF of ^{137}Cs were 0.14 and 0.097, respectively (Table VI-6, Table VI-7).

VI-5.2. Transfer factors of ^{90}Sr and ^{137}Cs from soil to sweet potato

Besides rice, the uptake of another major starch crop, sweet potato, has been studied. During a field study carried out in 1982-83, samples of soil and sweet potato were taken from eight cities and counties in Taiwan, China and analysed to measure activity concentrations of ^{90}Sr and ^{137}Cs [VI-11]. The average TF of ^{90}Sr and ^{137}Cs from soil to sweet potato determined from these measurements were 0.55 and 0.095 respectively (see Table VI-8).

VI-5.3. Transfer factors of ^{137}Cs from soil to grass

In a field study carried out in 1994-95, samples of soil and grass were taken from five sites in northern Taiwan, China, and analysed to measure the activity concentrations of ^{137}Cs, ^{60}Co and ^{54}Mn [VI-12]. The TF (DM) of ^{137}Cs from soil to grass determined from these observations were 0.36 (0.25–0.61) for *Eleusine indica* (L.) Gaertn. (Site A) and 0.25 (0.06–0.63) for *Miscanthus floridulus* (Labill.) Warb. ex Schum. and Laut. (Sites B to F), respectively. The TF of ^{60}Co and ^{54}Mn for the same grass varieties were 0.45 (0.14–0.92) and 0.29 (0.04–0.75) and 0.40 and 2.2 (1.0–3.3), respectively (see Table VI-9).

VI-5.4. Transfer factors of ^{137}Cs for mushrooms

During a field study carried out in 1994, sawdust and mushroom samples were taken from seven cities in Taiwan, China, and analysed to measure the activity concentrations of ^{137}Cs [VI-13]. The estimated TF of ^{137}Cs from sawdust to mushroom varied from <3.8 to around 10 (see Table VI-10).

VI-5.5. Transfer Factors of ^{137}Cs from soil to tea leaves

During a field study carried out in 1995, soil and tea leaf samples were taken from two sites in northern Taiwan, China, and analyzed to measure the activity concentrations of ^{137}Cs. The TF of ^{137}Cs from soil to tea leaves (DM basis) were 0.005 4–0.008 2 (Table VI-11).

TABLE VI-5. TRANSFER FACTORS OF CS-137 FOR VARIOUS VEGETABLES

Experiment	Vegetable	Transfer factor	
		Leaf	Root
TRMC Greenhouse	Chinese cabbage	0.042 0.002 9 0.001 1 0.089	0.01
TRMC Greenhouse	Water convolvulus	0.007 0 0.003 7 0.007 5 0.029	0.083
Field	Cabbage	0.023	0.028
Field	*Brassica chinensis* (Bailey)	0.004 7	0.01
Field	Sweet potato		0.363

TABLE VI-6. TRANSFER FACTORS OF SR-90 FOR RICE (FIELD STUDY)

Location	No. of samples	Activity concentration in soil (Bq/kg, DM)	Activity concentration (Bq/kg, DM)		Transfer factor	
			Brown rice	Polished rice	Brown rice	Polished rice
Taoyuan	2	0.47	0.044	0.011	0.094	0.023
Hsinchu	2	1.39	0.037	0.007	0.027	0.0050
Miaoli	2	0.90	0.037	0.011	0.041	0.012
Taichung	2	0.36	0.080	0.026	0.22	0.072
Changhwa	3	0.24	0.017	0.018	0.071	0.075
Nantou	2	0.43	0.044	0.024	0.10	0.056
Yunlin	4	0.72	0.020	0.009	0.028	0.013
Chiayi	3	0.42	0.027	0.012	0.065	0.029
Tainan	4	0.94	0.039	0.006	0.041	0.0064
Kaohsiung	4	0.32	0.035	0.014	0.11	0.044
Pingtung	4	0.34	0.030	0.009	0.088	0.026
Taitung	1	0.25	0.037	0.022	0.15	0.088
Average (AM)	n.a. [a]	n.a.	n.a.	n.a.	0.086	0.037
GM (GSD) [b]					0.07 (16)	0.03 (44)

[a] n.a.: Not applicable.
[b] Calculated by J. Twining in 2021; GM (GSD): Geometric Mean (Geometric Standard Deviation).

TABLE VI-7. TRANSFER FACTORS OF CS-137 FOR RICE (FIELD STUDY)

Location	No. of samples	Activity concentration in soil (Bq/kg, DM)	Activity concentration (Bq/kg, DM)		Transfer factor	
			Brown rice	Polished rice	Brown rice	Polished rice
Taoyuan	2	2.7	0.52	0.40	0.19	0.15
Hsinchu	2	2.6	0.69	0.49	0.27	0.19
Miaoli	2	4.1	0.29	0.20	0.071	0.049
Taichung	2	2.4	0.41	0.40	0.17	0.17
Changhwa	3	2.8	0.31	0.24	0.11	0.086
Nantou	2	4.6	0.72	0.39	0.16	0.085
Yunlin	4	1.3	0.16	0.12	0.12	0.092
Chiayi	3	1.5	0.22	0.15	0.15	0.10
Tainan	4	2.0	0.17	0.06	0.085	0.030
Kaohsiung	4	2.3	0.23	0.21	0.10	0.091
Pingtung	4	4.0	0.47	0.28	0.12	0.070
Taitung	1	5.3	0.44	0.31	0.083	0.058
Average (AM)	n.a. [a]	n.a.	n.a.	n.a.	0.14	0.097
GM (GSD) [b]					0.13 (9.3)	0.087 (13.2)

[a] n.a.: Not applicable.
[b] Calculated by J. Twining in 2021. GM (GSD): Geometric Mean (Geometric Standard Deviation).

TABLE VI-8. TRANSFER FACTORS OF CS-137 AND SR-90 FOR SWEET POTATOES (FIELD STUDY)

Location	Cs-137			Sr-90		
	Activity concentration (Bq/kg)		Transfer factor	Activity concentration (Bq/kg)		Transfer factor
	Soil (DM)	Sweet potato (FM [a])		Soil (DM)	Sweet potato (FM)	
Taipei	39.6	1.32	0.033	2.63	2.76	1.0
Taoyuan	4.02	0.24	0.060	0.39	0.17	0.44
Miaoli	2.93	0.12	0.041	0.96	0.61	0.64
Nantou	2.62	0.24	0.092	0.23	0.14	0.61
Chiayi	2.36	0.07	0.030	0.74	0.07	0.09
Kaohsiung	1.02	0.37	0.36	0.20	0.07	0.35
Hualien	4.11	0.33	0.080	0.37	0.39	1.1
Penghu	2.52	0.15	0.060	0.39	0.05	0.13
Average (AM)			0.09			0.55
GM (GSD) [b]			0.07 (10.4)			0.41 (3.56)

[a] FM: Fresh mass.
[b] Calculated by J. Twining in 2021. GM (GSD): Geometric Mean (Geometric Standard Deviation).

TABLE VI-9. TRANSFER FACTORS (DM) OF CS-137, CO-60 AND MN-54 FROM SOIL TO GRASS

Site	Soil characteristics		Transfer factor		
	H_2O (%)	pH	Cs-137	Co-60	Mn-54
A	9.80	5.15	0.36 (0.25–0.61)	0.46 (0.14–0.92)	0.40
B	17.9	4.18	0.30 (0.06–0.63)	0.43 (0.06–0.75)	—
C	11.0	4.83	0.42 (0.13–0.60)	0.42 (0.10–0.68)	1.0
D	11.6	6.90	0.14 (0.05–0.30)	0.16 (0.04–0.28)	2.9 (2.4–3.3)
E	3.54	7.29	0.22 (0.21–0.23)	— [a]	—
F	18.2	5.21	0.15 (0.06–0.3)	0.16 (0.07–0.25)	—

[a] —: Data not available.

TABLE VI-10. TRANSFER FACTORS (DM) OF ^{137}CS FROM SAWDUST TO MUSHROOMS

Species	No. of samples	Activity concentration (Bq/kg DM) [a]		Transfer factor
		Mushroom	Sawdust	
Flamulina velutipes	6	<1.0	<0.10	n.a.
Ganoderma lucidum	4	1.3 ± 0.3	0.13 ± 0.02	10.2
Lentinula edodes	23	<1.3	0.34 ± 0.04	<3.8

[a] For the calculation of average concentration, values described as 'limit of detection' were also included.

TABLE VI-11. TRANSFER FACTORS (DM) OF CS-137 FOR TEA LEAVES, NORTHERN TAIWAN, CHINA (FIELD STUDY)

Site	Activity concentration of Cs-137 (Bq/kg, DM)				Transfer factor		
	Soil	Leaf	Stem	Root	Leaf	Stem	Root
A	69	0.37	0.47	0.65	0.0054	0.0068	0.0094
B	22	0.18	— [a]	—	0.0082	—	—

[a] —: Data not available.

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ANNEX VII.

STUDIES ON RADIONUCLIDE TRANSFER FROM SOIL TO THE FOOD CHAIN OF MAN IN TROPICAL ENVIRONMENT OF BANGLADESH

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VII-1. OBJECTIVE OF THE STUDY

The main objective of this study was to determine radionuclide transfer parameters from soil to plants in the human food chain in the tropical environment of Bangladesh to provide data for dose assessment models. These transfer parameters are required in the assessment of the radiation exposure to humans associated with the releases of radionuclides from nuclear facilities by means of radiological assessment models [VII-1]. The determination of the TF of ^{137}Cs and ^{90}Sr from soil to plants and crops in pot experiments was carried out under the IAEA Coordinated Research Project "Radionuclide Transfer from Air, Soil, and Freshwater to the Food chain of Man in Tropical and Sub-tropical Environments".

VII-2. UPTAKE OF ^{137}CS AND ^{90}SR BY PLANTS AND CROPS FROM SOIL

VII-2.1. Experimental methods

A pot experiment was carried out to determine the TF from soil to plants and crops. Bulk soil samples down to a depth of 15 cm were collected and air-dried, ground and screened to pass through a 2 mm sieve and then mixed thoroughly to produce composite samples. Carrier-free radioactive solutions of ^{137}Cs ($CsCl_2$) and ^{90}Sr ($SrCl_2$) were obtained from Amersham, UK. The solutions (600 Bq per kg (dry mass, DM) of soil of ^{137}Cs and 400 Bq per kg (dry mass, DM) of soil of ^{90}Sr) were mixed with soil separately in earthen pots of semi-conical shape with an upper diameter of 29 cm, lower diameter of 18 cm and height of 22 cm. Eight pots were used for each radionuclide; each pot was internally lined with thin polythene sheets to prevent the radioactivity contamination of the pot and filled with 10 kg of treated soil. The plants and crops used in the experiments were: grass, peanuts, beans, tomatoes, spinach, cabbage, rice and pineapple. Peanuts, beans and spinach were grown from seeds in the pots, while 15-day old tomato and cabbage seedlings, uniform in size, several grass seedlings and one pineapple seedling were planted in the pots. Growth conditions adopted in the experiment were 12-hour days at a temperature of 30°C and 12-hour nights at a temperature of 25°C. All pots were irrigated with water and fertilizers were mixed thoroughly with the soil. The fertilizers were applied as per recommendation of the Bangladesh Agricultural Research Council [VII-2]. After allowing the plants to grow to maturity under normal environmental conditions, they were harvested for analysis of ^{137}Cs and ^{90}Sr. The experimental details were in line with the agreed CRP protocols (see Annex II above).

VII-2.2. Analysis of soil and plants

Activity concentrations of ^{137}Cs in soil and plant samples were determined by gamma spectrometry using a HPGe detector with a resolution of 2 keV (FWHM) at the 1332 keV γ-ray of ^{60}Co and a relative efficiency of 20%. The γ-ray spectra were accumulated using a 4096 channel analyzer (Canberra 35plus). The efficiency of the detector was measured using standard radioactive sources with the same geometry as the samples [VII-2]. The activity concentrations of ^{90}Sr in soil and plants were determined by low-level β-counting of its daughter nuclide ^{90}Y,

separated from ^{90}Sr by radiochemical techniques [VII-3, VII-4]. The Cherenkov radiation produced by the high-energy β-particle of ^{90}Y was measured using a Packard Tri-Carb liquid scintillation counter [VII-4]. The time of measuring was chosen so that the relative error of counting was less than ± 5%. Quality control was assured by determining ^{137}Cs and ^{90}Sr using the IAEA's standard reference materials (Soil-375 and Clover-156).

The physical properties of soil such as the percentage of moisture, bulk density and particle size distribution were measured by standard methods as described by Piper [VII-5]. The textural class was determined from the triangular coordinates as devised by the United States Department of Agriculture (USDA). The pH, organic matter, cation exchange capacity (CEC) and exchangeable cations (Na^+, K^+, Ca^{++}, Mg^{++}) of soil were determined using standard methods [VII-5]. The potassium and calcium contents in plants were measured, after chemical separation, by standard procedures [VII-5]. X-ray diffraction was employed for the determination of the mineral composition [VII-2].

The soil-to-plant TF were determined according to the CRP protocol (see Annex II of this this Supplementary File):

$$\mathrm{TF}_{\mathrm{grass}} = \frac{\text{Activity concentration in grass } (\frac{Bq}{kg}, \text{DM})}{\text{Activity concentration in upper 10 cm of soil } (\frac{Bq}{kg}, \text{DM})} \quad \text{(VII-1)}$$

$$\mathrm{TF}_{\text{other crops}} = \frac{\text{Activity concentration in crop } (\frac{Bq}{kg}, \text{DM})}{\text{Activity concentration in upper 20 cm of soil } (\frac{Bq}{kg}, \text{DM})} \quad \text{(VII-2)}$$

VII-2.3. Results and discussion

The physical and chemical properties of the soil used in the study are presented in Table VII-1.

The average values of the TF of ^{137}Cs and ^{90}Sr and of the levels of calcium and potassium in plants and crops are given in Table VII-2. The observed TF are in the range 0.02–0.98 and 0.18–1.31 for ^{137}Cs and ^{90}Sr, respectively. Our results show significant variations of the TF with plant species. The highest ^{137}Cs transfer values were obtained for cabbage and spinach. In the case of ^{90}Sr, the highest TF were obtained for spinach and cabbage. The lowest ^{137}Cs and ^{90}Sr transfer values are found in grass and pineapple, respectively. The TF of ^{137}Cs and ^{90}Sr observed in the plants and crops are generally higher than those reported in the literature [VII-1, VII-6]. These differences may be due to different soil properties and other factors because it is well known that the uptake of radionuclides by plants/crops from the soil depends on the plant species as well as the soil characteristics, such as clay content, pH, CEC and organic matter [VII-1].

TABLE VII-1. PHYSICAL AND CHEMICAL PROPERTIES OF SOIL

Physical properties		Chemical properties	
Moisture:	6.95%	pH:	7.5 (Soil:$CaCl_2$ = 1:2.5)
Bulk density:	1.34 g/cc	Organic matter:	0.85%
Particle size analysis:		CEC:	12.92 meq/100 g soil
Sand:	41%	Glow-loss:	9.12%
Clay:	28%	Exchangeable cations:	
Silt:	31%	Ca:	10.3 meq/100 g soil
Textural class:	Sandy loam	Mg:	0.99 meq/100 g soil
Clay minerals	Kaolinite and Illite	K:	0.51 meq/100 g soil
		Na:	0.96 meq/100 g soil

TABLE VII-2. TRANSFER FACTORS OF CS-137 AND SR-90, POTASSIUM AND CALCIUM CONTENTS IN DIFFERENT CROPS OR PLANTS

Crop	TF (DM) [a]		K (mg/kg)	Ca (mg/kg)
	Cs-137	Sr-90		
Rice	0.11 ± 0.09	0.39 ± 0.08	1253	110
Beans	0.09 ± 0.03	0.34 ± 0.06	20716	4360
Peanuts	0.32 ± 0.08	0.24 ± 0.06	7935	2941
Pineapple	0.04 ± 0.002	0.18 ± 0.02	12346	3678
Cabbage	0.98 ± 0.11	1.22 ± 0.12	14789	6142
Tomato	0.11 ± 0.01	0.46 ± 0.09	30347	4208
Spinach	0.89 ± 0.30	1.31 ± 0.15	31462	8495
Grass	0.02 ± 0.001	0.69 ± 0.07	2345	2789

[a] Arithmetic Mean ± Standard Deviation.

VII-3. CONCLUSIONS

No seasonal variations in soil to plant TF were observed. The TF were at least one order of magnitude higher than reported values from Refs. [VII-1, VII-6]. The TF for radiological assessment models found in the literature are not appropriate for tropical and sub-tropical environments as observed in the present study.

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ANNEX VIII.

RADIONUCLIDE TRANSFER FACTORS FROM AIR, SOIL AND FRESHWATER TO THE FOOD CHAIN OF MAN IN MONSOON TROPICAL CONDITION OF VIETNAM

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VIII-1. OBJECTIVES

To calculate discharge limits for radioactive effluents and to assess the radiation dose to man related to discharges of radionuclides from nuclear facilities, data on radionuclide transfer parameters from the environment to the food chain of man are required. Such data depend strongly on climatic, geographic, environmental and pedological conditions. For temperate environments data are fairly well established [VIII-1]. However, data are very scarce for tropical and sub-tropical zones.

The general objective of this study is to obtain transfer parameters of critical radionuclides from air, soil and freshwater to the food chain of man in monsoon-tropical environments of Vietnam.

During the period 1993 to 1997 the specific objectives of this project were focused on an IAEA Coordinated Research Project (CRP). They included:

(1) Measurements of the dry deposition velocities of atmospheric aerosols carrying ^{7}Be;
(2) Measurements of soil to plant and freshwater to fish TF for ^{137}Cs and ^{90}Sr at environmental levels. These measurements were based on previous atmospheric deposition of nuclear weapons fall out and/or accidental releases;
(3) Measurements of soil to plant TF of ^{60}Co, ^{65}Zn, ^{85}Sr and ^{134}Cs based on radiotracer experiments with large pots, conducted outdoors;
(4) Measurements of freshwater to fish TF of ^{134}Cs based on tracer experiments.

The soil types (alluvial and old alluvial soil, podzolic soil, ferralitic soil, sandy soil of humid tropics), crops (rice, bean, carrot, white radish, potato, cabbage, cucumber, lettuce, tomato, etc.) and fish species (tilapia, common carp) selected for this work are amongst the most common ones in Vietnam.

Methods and procedures of the experiments followed the final version of the protocols for the measurement of transfer parameter, developed during the CRP (see Annexes II and III above).

VIII-2. EXPERIMENTAL SET UP

VIII-2.1. Measurements of the dry deposition velocities of atmospheric ^{7}Be

Models for the prediction of the deposition of materials from the atmosphere require the knowledge of the dry deposition velocity (V_g) of the aerosols carrying the material under study. The value of V_g (cm/s) is defined as the ratio of the deposition D (1/cm^2 s) to the atmospheric concentration A (1/cm^3). If V_g values are known and A can be measured or calculated from source term data, the deposition can be calculated using the equation:

$$D = \sum A_i \times V_g \qquad \text{(VIII-1)}$$

The locations of the selected experimental sites range from 11° 57' N, 108° 26' E to 10° 02' N, 105° 47' E. Two air-sampling stations were set up in this region; both aerosol and fallout samples were collected monthly. The locations of the air sampling sites were selected considering the existence of several months without any rainfall.

Particulate radioactivity was collected from about 100 000 m^3 of air on a 0.48 m^2 chlorinated vinyl polychloride Petrianow filter FPP-15-1.7 using an air sampler 12-UC-34 with a flow rate of 760 m^3/h. The intake was 1.5 m above ground. The filters were compressed into pellets of 36 mm diameter and 10 mm thickness for gamma spectrum measurement.

Dry fallout was collected throughout the month in three stainless-steel trays, each with a cross-section of 0.4 m^2. The resuspension of dry fallout particles was prevented by adding distilled water with a layer thickness of about 1 cm. Samples were passed through a filter to separate suspended and dissolved fractions. The filtrate was subsequently evaporated in vacuum.

VIII-2.2. Determination of soil-to-plant TF for ^{137}Cs and ^{90}Sr at environmental activity concentrations

VIII-2.2.1. Sample collection and preparation

The methods used for soil sampling and preparation were similar to those given in references [VIII-2–VIII-5]. At various locations in Vietnam, ten soil cores, with a diameter of 10 cm, down to the depth of the rooting zone were taken of each site. They represented a total surface area of about 800 cm^2; the mass of each sample was about 4 to 5 kg. At the laboratory the samples were spread on trays and allowed to dry; thereafter they were sieved until only stones and organic residues remained. A brief description of the sites is given below (Section VIII-4 below).

For each crop sample, 10 kg fresh mass (FM) were collected. The samples were washed with water without any detergent to remove soil and other adhering material and only the edible part was retained for analyses after drying at 105°C and ashing at 400°C.

VIII-2.2.2. Radiochemical analysis of food and environmental samples

The radiochemical methods for separation and determination of some specific nuclides are shown in Figures VIII-1–VIII-3. As it appears from the figures, the separation and determination of radiostrontium in various materials occurred by oxalate precipitation. The separation of radiocaesium was done by precipitation in the form of $Cs_2Zn_3[Fe(CN)_6]_2$ or $Cs_2Co_3[Fe(CN)_6]_2$ and by using KCFC adsorbent.

VIII-3. DETERMINATION OF RADIONUCLIDES

The activity concentrations of ^{7}Be and ^{137}Cs were determined by high-resolution gamma spectrometry. Counting times were in the range of 50 000–70 000 seconds. The activity concentration of ^{90}Sr was determined by β radiometry after chemical separation. Details are shown in Table VIII-1.

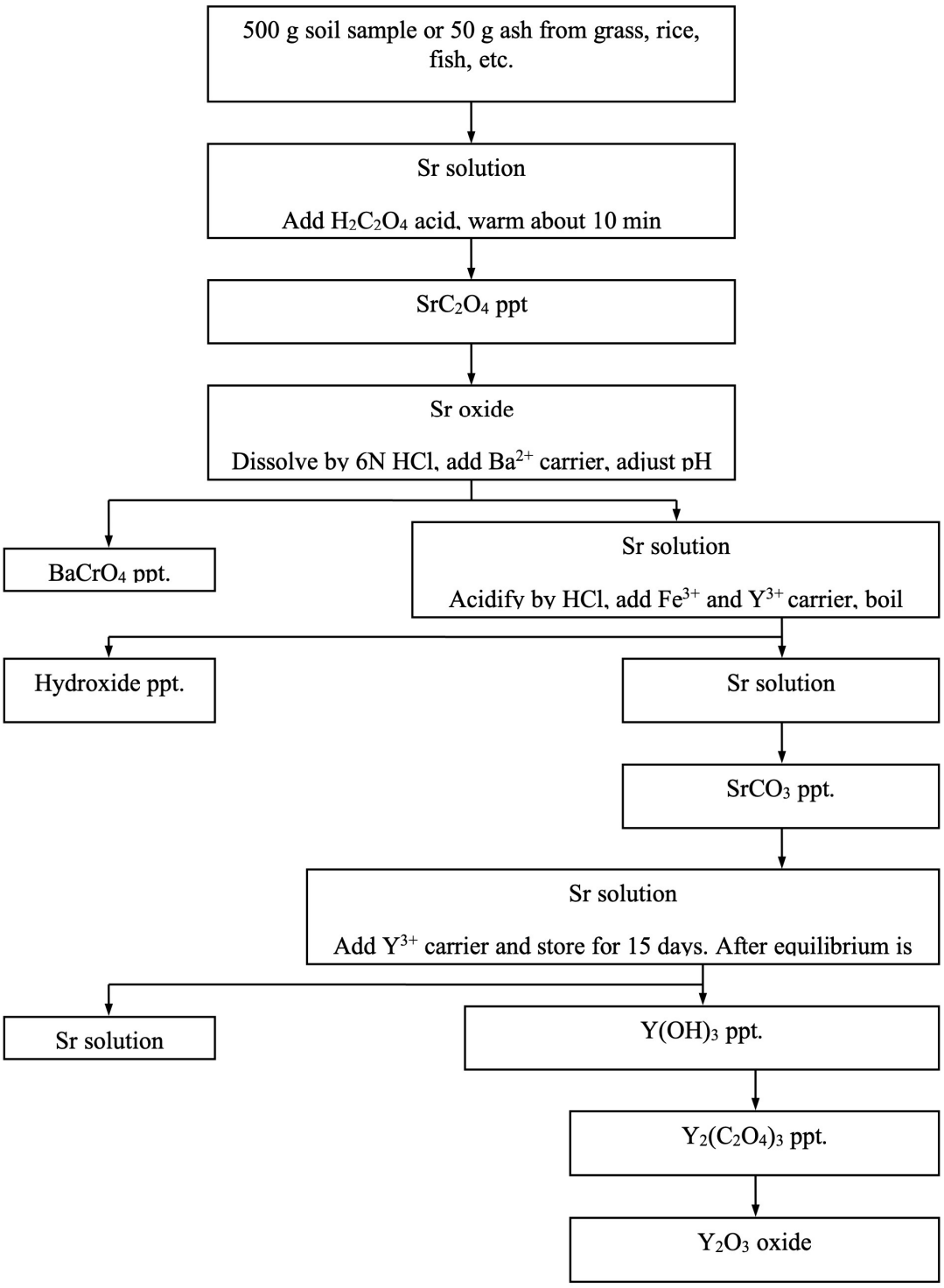

FIG. VIII-1. Scheme of separation of ^{90}Sr from soil, plant and food samples.

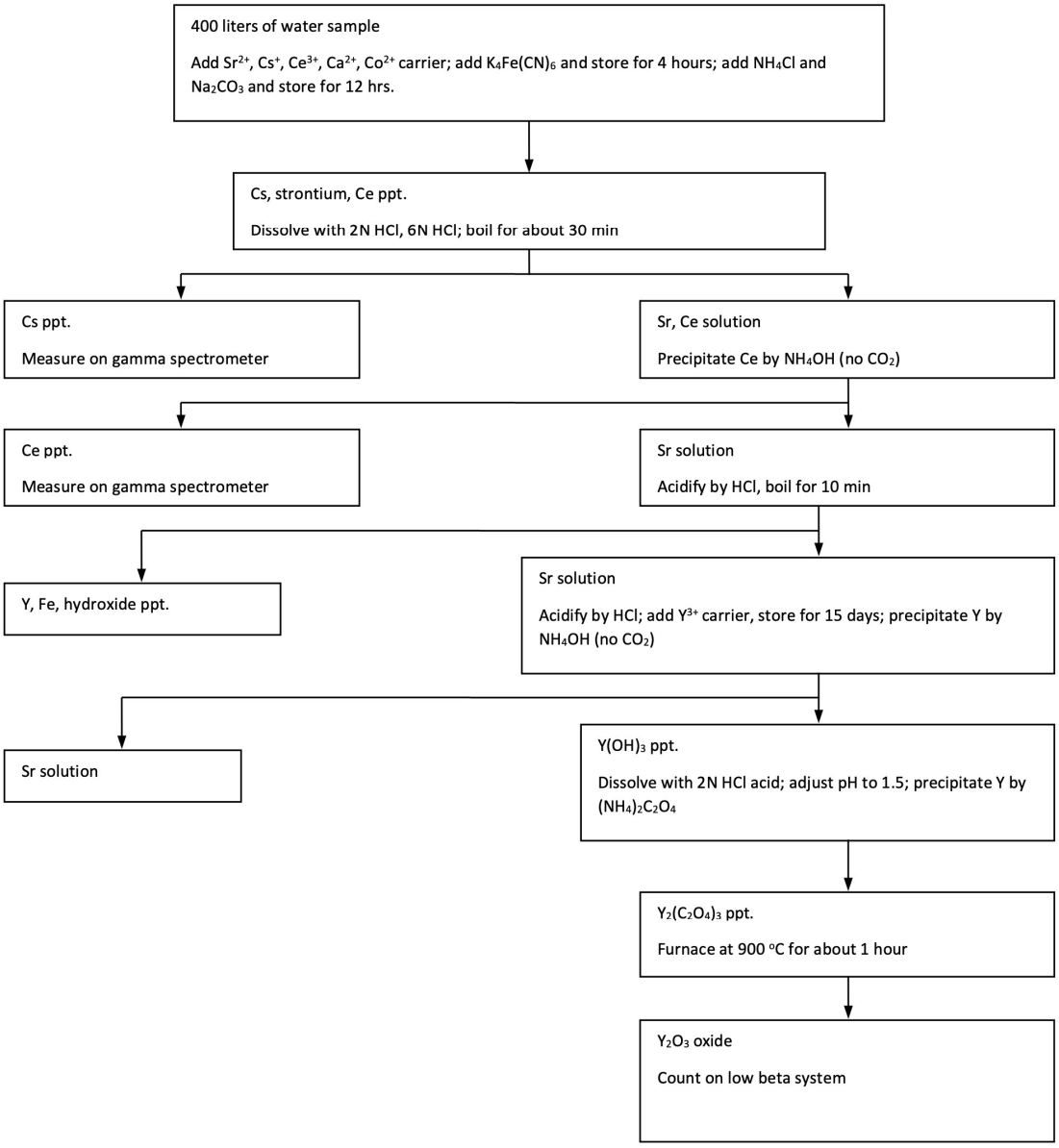

FIG. VIII-2. Scheme of separation of ^{137}Cs, ^{90}Sr and ^{144}Ce from water samples.

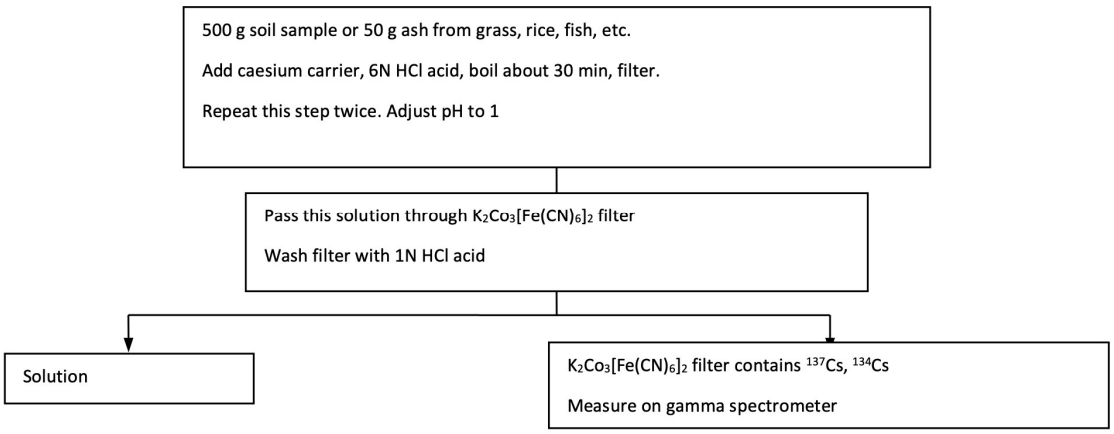

FIG. VIII-3. Scheme of rapid separation of ^{137}Cs, ^{134}Cs from soil and plant samples.

TABLE VIII-1. TECHNICAL CHARACTERISTICS OF LOW-LEVEL COUNTING SYSTEMS

System	Detector, type of shield	Background (1/s)	Counting efficiency	LOD (Bq) [a]
Low-background γ-ray spectrometer	HpGe det. sensitivity vol. of 71 cm^3 Shield: 3 mm Al, 3 mm Cu, 4 cm Fe, 10 cm Pb Size: 50 cm × 50 cm × 50 cm	1.7 (integ. from 100-2000 keV)	Relative eff. of 15% and 1.92 keV FWHM at 1332.5 keV	0.01
Low background anticoincidence β-counting system	Plastic scintillation detector of 4 cm diameter Shield: 5 mm Al, 5 mm Cu, 7 cm Fe, 5 cm Pb Size: Φ 20 cm, h 48 cm	0.025	25% for source of K-40, diameter 2.5 cm	0.03

[a] LOD: Limit of Detection.

TABLE VIII-2. PATTERNS OF PARTICLE SIZE DISTRIBUTION OF CS-137 IN SOIL SAMPLES

Soil type	Location	Coordinates	Percentage of total weight of fractions <10μm (%)	Total concentration of Cs-137 in fractions <10μm (Bq/kg)	Concentration of Cs-137 in the whole soil sample (Bq/kg)	
					Calculated	Determined
Coastal sandy soil of the humid tropics	Danang	16° 02' N 108° 12' E	24.5	38.97	9.54	9.55
Podzolic soil	Dalat	11° 57' N; 108° 26' E	14.7	18.33	2.70	3.12
Ultrabasic ferralitic soil	Thanhhoa	19°48' N; 105° 46'E	41.0	13.84	5.67	6.07
Red-yellow soil in basaltic	Ductrong-Baoloc	11° 28' N; 107° 48'E	38.5	3.50	1.35	1.63
Alluvial soil of the Mekong river	Cantho	10° 02' N; 105° 47'E	11.3	8.18	0.92	1.12

VIII-4. AN IMPROVED TECHNIQUE FOR THE DETERMINATION OF ^{137}CS IN SOIL SAMPLES

The existing methods to determine ^{137}Cs in environmental samples with concentrations ≤1 Bq/kg appeared not to be suitable. Therefore, a new, more sensitive method was developed based on a separation of soil particles according to their grain size distribution followed by high-resolution gamma spectrometry.

The various fractions of soil samples were dried crushed by hand and sieved at 1 mm. For further separation a shaker (Endecotts EFL2 mK3 Test sieve, France) comprising a set of 7 sieves and a pan was used. Results of these mechanical analyses obtained with experimental soil samples are shown in Figure VIII-4 and Table VIII-2.

In all samples, the medium-fine loam and clay fractions contained more than 80% of the ^{137}Cs. Thus, with the new method an enrichment factor of about 5 can be reached for ^{137}Cs.

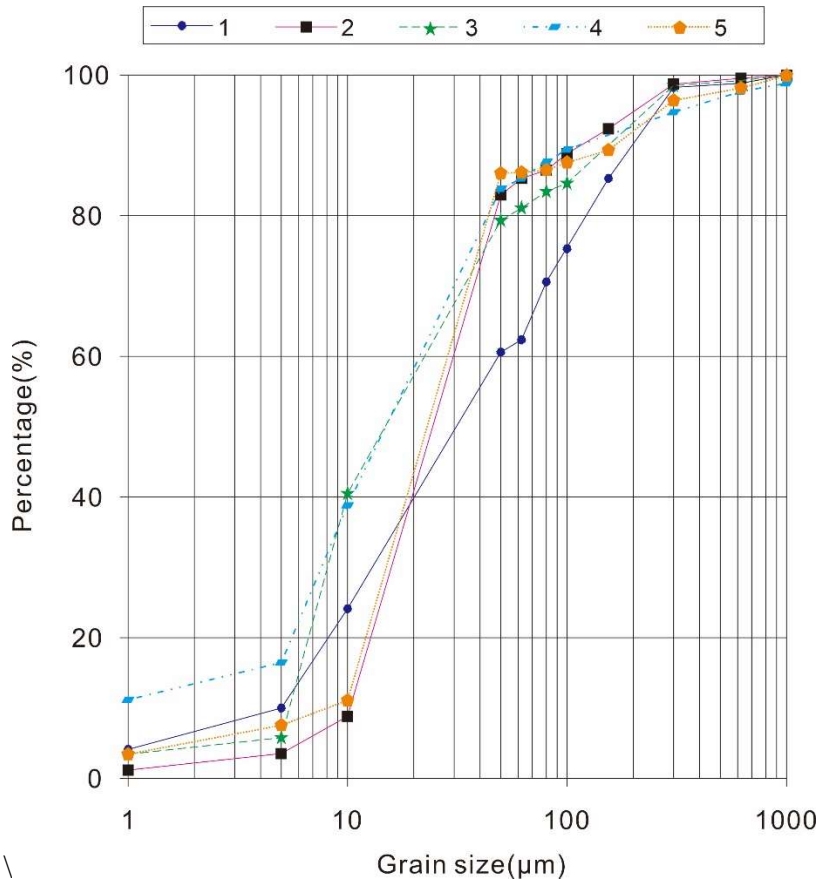

FIG. VIII-4. Grain size distribution of Cs-137 in soil samples from Table VIII-2.

VIII-4.1. Determination of soil to plant TF for ^{60}Co, ^{65}Zn, ^{85}Sr and ^{134}Cs by outdoor tracer experiments

The main characteristics of the experiment were:

(a) Radionuclides used: ^{60}Co, ^{65}Zn, ^{85}Sr and ^{134}Cs (the radionuclides were added as chlorides, with carrier);
(b) Levels of soil labelling were: ^{60}Co: 15 000 Bq/kg dry mass (DM); ^{65}Zn: 30 000 Bq/kg DM; ^{85}Sr: 45 000 Bq/kg DM; ^{134}Cs: 20 000 Bq/kg DM;
(c) Crops used: rice, black beans, carrots, white radish, potatoes, cabbage, cucumbers, lettuce and tomatoes; and
(d) Type of experiments: outdoor experiments with plastic large pots of 71 L of volume (diameter: 60 cm; height: 25 cm), containing about 50 kg of soil per pot.

A concrete mixer (Paribat S.A. AS130) was used to mix the soil with the tracer. The experiments were supervised by local agricultural experts to guarantee that they reflected normal agricultural practice. Further details on the experimental conditions such as radionuclide concentrations, farming regimes, types of soil, time of soil treatment, as well as soil parameters such as pH, exchangeable potassium and calcium concentrations in soil, organic matter content, are included in the database of the CRP. For the elemental and other analyses standard methods were applied; results are shown in Table VIII-3.

TABLE VIII-3. ELEMENTAL COMPOSITION OF EXPERIMENTAL SOILS (IN PPM DM)

Element	Soil type, crop			
	Alluvial soil, rice	Podzolic soil vegetables	Ferralitic soil, cash crop, fruit tree	Old alluvial soil rice
Na	4 000	490	340	618
Mg	19 700	27 000	18 300	10 000
Al	140 000	135 000	140 000	51 000
K	18 400	2 000	4 300	3 600
Ca	8 000	2 600	6 000	8 000
Sc	14	17	25	8
Ti	5600	3 770	4 650	4 600
V	156	136	127	77
Cr	51	34	114	37
Mn	500	250	1 000	370
Fe	30 000	56 000	100 000	19 000
Co	12	2.5	22	5.3
Cu	60	20	16	12
Zn	200	109	200	100
As	8.0	2.5	2.0	5.6
Se	1.5	0.4	0.3	1.4
Br	6.2	5.9	7.0	4.6
Rb	115	25	25	20
Mo	1.9	2.1	3.0	2.0
Sn	2.0	2.2	5.1	2.8
Sb	0.3	0.7	0.9	0.8
I	0.6	0.4	0.4	0.4
Cs	5.0	3.3	2.0	4.3
Ba	402	290	250	138
La	36	14	28	27
Ce	97	25	70	62
Eu	1.7	0.2	0.8	0.6
Tb	1.1	0.5	0.7	0.9
Yb	2.5	1.3	2.2	2.6
Lu	0.4	0.3	0.4	0.6
Hf	6	4	5	4
W	3.0	2.1	2.5	2.6
Th	12	22	14	13
U	3	5	3	4

VIII-4.2. Determination of freshwater to fish TF for ^{137}Cs and ^{90}Sr at environmental activity concentrations

Fish samples of 5 kg FM were collected from various locations in Vietnam and washed with water and blotted with a filter paper. Only the edible part was used. Each sample was placed in a porcelain dish. After being dried at 105°C to constant weight, the samples were ashed in an electric muffle furnace at 400°C.

Samples of 400 L of lake water and river water were collected for analysis on the same day as the fish samples. The water samples were acidified to pH = 4 by adding concentrated nitric acid. Strontium, caesium, cerium, calcium and cobalt carriers were added to the filtered water samples.

VIII-4.3. Determination of freshwater to fish TF for ^{134}Cs by radiotracer experiments

The experiments focused on determining TF of ^{134}Cs from freshwater to some common fish species under conditions that are comparable to natural conditions. For this purpose, a system of experimental cement tanks was set up in cooperation with Quang Hiep experimental farm for freshwater fish, Research Institute for Aquaculture No.2. The system consists of three 12 000 L tanks (dimensions: 3 m × 3 m × 1.4 m), one for acclimatization and two replicates for experimental exposure. The underground part of the tanks was 0.8 m. The tanks contained a sediment layer of 10 cm, while the water depth was 1.3 m.

The chemical and elemental compositions of natural lake water and of the experimental tank water are shown in Tables VIII-4 and VIII-5.

The optimum fish density was determined by the need for a good harvest (7 specimens per m^2). The activity concentration of ^{134}Cs in the experimental tanks was maintained at an activity concentration of 900 Bq/L. To achieve complete nutrition of the fish, formulated feed consisting of terrestrial grass and mixed bran was used.

A mobile multichannel analyzer supporting a scintillation detector 16 cm in diameter and 23 cm in length with a 10.5 cm diameter by a 14.5 cm deep centre well was built to facilitate in-situ measurements of uptake rates of ^{134}Cs in fish.

VIII-5. RESULTS AND DISCUSSIONS

VIII-5.1. Dry deposition velocity of ^{7}Be

The data used for the calculation of V_g contain 29 monthly measurements of ^{7}Be in the atmosphere and dry deposits during the dry periods of 1992–1997. The measured V_g values range from 0.13 to 0.97 (cm/s).

VIII-5.2. Transfer factors of ^{137}Cs and ^{90}Sr for environmental samples

Food and environmental samples were collected at different locations of Vietnam. The radionuclide concentrations in these samples were determined and the results of TF derived from these observations are given in Tables VIII-6 and VIII-7. The soil types and other soil characteristics are also included in these tables.

VIII-5.3. Soil to plant TF derived from pot experiments

During the project, 344 soil-to-plant TF were determined. The mean values (on DM basis), are shown in Table VIII-7 and in Fig. VIII-5. The water content of fresh products were 39.1% for rice, 52.9% for black beans, 89.3% for carrots and 86.0% for potatoes; for cabbage, cucumber, lettuce, white radish and tomato values range from 92.3% to 96.5%. No difference in water contents was detected between crops from fields and pots.

VIII-5.4. Speciation of radionuclides added to soil

The chemical form of radionuclides in soils varies with time. To determine these chemical forms, often called speciation, sequential extraction techniques can be used. The scheme which was used in this study is shown in Table VIII-8.

Results are shown in Table VIII-9. From Table VIII-9 it can be concluded that it takes about 1 to 3 months to reach equilibrium between the applied radionuclides and the soil.

TABLE VIII-4. CHEMICAL COMPOSITION OF WATER IN NATURAL WATER AND TANKS

Constituent	Concentration	
	Lake water	Water of the experimental tanks
Temperature (°C)	23.7 – 26.2	≈ 26
pH	7.18	6.90
Total dissolved solid (TDS) (mg/L):		
At 105°C	42.78	56.50
At 400°C	28.96	37.60
Electrical conductivity (µs/cm)	48.00	60.70
Dissolved oxygen (DO) (mg/L)	7.52	7.84
Hardness (mg-e/L)	0.22	0.37
NH_{4+} (mg/L)	0.04	0.05
Fe^{2+} (mg/L)	0.08	0.10
Fe^{3+} (mg/L)	0.12	0.13
NO_{3-} (mg/L)	2.00	2.48
PO_4^{3-} (mg/L)	0.01	0.02
SiO_3^{2-} (mg/L)	0.67	0.85
Ca^{2+} (mg/L)	3.21	4.80
Mg^{2+} (mg/L)	0.78	1.65
Na^{+} (mg/L)	4.50	4.50
K^{+} (mg/L)	1.50	3.40
HCO_3^{-} (mg/L)	20.85	32.94
CO_3^{2-} (mg/L)	0.00	0.00
SO_4^{2-} (mg/L)	0.45	0.76
Cl^{-} (mg/L)	3.97	2.84

TABLE VIII-5. ELEMENTAL COMPOSITION OF WATER IN TANKS

Element	Concentration (µg/l)	Element	Concentration (µg/l)
Al	571	Sn	0.06
Sc	0.05	Sb	0.05
Ti	38.78	I	2.90
V	1.19	Cs	0.17
Cr	0.38	Ba	9.90
Mn	55.6	La	0.48
Co	0.30	Ce	0.82
Ni	1.4	Eu	0.01
Cu	1.6	Tb	0.001
Zn	11.3	Yb	0.019
As	0.70	Lu	0.003
Se	0.06	Hf	0.011
Br	2.63	W	0.26
Rb	1.78	Hg	1.10
Sr	12.80	Pb	2.0
Mo	0.04	Th	0.07
Cd	0.14	U	0.10

TABLE VIII-6. SOIL TO PLANT TRANSFER FACTORS (DM BASIS) DETERMINED IN THE FIELD ON NUCLEAR WEAPONS FALLOUT

Crop	Transfer factor	Main soil type	Exchangeable K	Exchangeable Ca	Farming type [a]	pH [b]	Organic matter
			Cs-137				
Rice	0.24	Alluvial and old alluvial	0.96	5.56	F	7.0	1.60
Amaranth	0.40	Podzolic	2.23	4.34	I	5.5	0.78
Mustard, chinese	0.20	Podzolic	2.23	4.34	I	5.5	0.78
Tea leaf	3.2	Ferralitic	0.26	2.20	I	4.9	1.17
French bean	0.014	Podzolic	2.23	4.34	I	5.5	0.78
Green bean	0.22	Sandy soil of humid tropics	0.38	4.82	I	6.5	0.96
Carrot	0.15	Podzolic	2.23	4.34	I	5.5	0.78
Cassave	0.20	Sandy soil of humid tropics	0.38	4.82	D	6.5	0.96
Radish	0.13	Podzolic	2.23	4.34	I	5.5	0.78
Potato	0.14	Podzolic	2.23	4.34	I	5.5	0.78
Cabbage	0.17	Podzolic	2.23	4.34	I	5.5	0.78
Cabbage lettuce	0.32	Podzolic	2.23	4.34	I	5.5	0.78
Lettuce	0.21	Podzolic	2.23	4.34	I	5.5	0.78
Spinach	0.11	Podzolic	2.23	4.34	I	5.5	0.78
Water cress	0.38	Podzolic	1.54	2.31	F	5.8	1.06
Coffee	0.025	Ferralitic	0.26	2.20	I	4.9	1,17
Tea leaf	3.6	Ferralitic	0.26	2.20	I	4.9	1.17

[a] F: flooded soils; I: irrigated soils; D: dry farming;

[b] pH measured in KCl or $CaCl_2$ solution.

TABLE VIII-7. AVERAGE SOIL TO PLANT TRANSFER FACTORS DERIVED FROM POT EXPERIMENTS

Product	Transfer factor (Bq/kg DM / Bq/kg dry soil) [a]			
	Co-60	Zn-65	Sr-85	Cs-134
Rice	0.010 ± 0.001	0.89 ± 0.09	0.093 ± 0.011	0.094 ± 0.009
Black bean	0.94 ± 0.94	1.6 ± 0.6	4.1 ± 1.3	0.57 ± 0.16
Carrot	0.072 ± 0.013	0.71 ± 0.21	1.2 ± 0.1	0.70 ± 0.16
White radish	0.17 ± 0.06	1.9 ± 0.3	2.8 ± 0.2	0.54 ± 0.10
Potato	0.37 ± 0.02	1.1 ± 0.3	0.7 ± 0.1	0.71 ± 0.25
Cabbage	0.11 ± 0.07	1.7 ± 0.6	2.5 ± 1.2	1.3 ± 0.3
Cucumber	0.55 ± 0.09	2.8 ± 0.4	2.6 ± 0.2	1.8 ± 0.2
Lettuce	0.11 ± 0.08	1.9 ± 0.8	6.2 ± 2.8	1.5 ± 0.6
Tomato	0.26 ± 0.11	1.4 ± 0.5	1.6 ± 1.5	0.72 ± 0.2

[a] Arithmetic Mean ± Standard Deviation.

TABLE VIII-8. SEQUENTIAL EXTRACTION SCHEME FOR THE DETERMINATION OF THE CHEMICAL FORM OF CO-60, ZN-65, SR-85 AND CS-134 IN SOIL [VIII-6]

Present forms	Reagent	Procedure
1. Soluble in water	Distilled water	Phase ratio (solid:solution) 1:5; stir for 3 minutes, centrifuge, filter through blue filter paper with pore diameter of about 1.3 µm. Bottle filtrate in polyethylene container and measure activity on gamma spectrometer.
2. Exchangeable	1 N ammonium acetate solution	Phase ratio 1:10, stir for 1 hour and then continue in the same way as for the first step.
3. Soluble in dilute acid	1 N chlorohydric acid solution	Same procedure as for the second step

TABLE VIII-9. CHEMICAL FORM OF RADIONUCLIDES AS A FUNCTION OF THE TIME ELAPSED SINCE LABELLING SOIL (%)

Radionuclide	Time after labelling (d)	Chemical form		
		Soluble in water	Exchangeable and soluble in diluted acid	Sparingly soluble
Co-60	3.0	0.14	99.9	0.0
	10.3	0.34	98.8	0.89
	45.0	0.92	63.7	35.4
	94.0	0.27	55.0	44.7
	967	1.87	57.8	40.4
Zn-65	3.0	0.05	96.7	3.24
	10.3	0.05	78.1	21.9
	45.0	0.09	63.9	36.0
	94.0	0.04	53.0	46.9
	967	0.04	50.5	49.4
Sr-85	3.0	13.5	86.5	0.0
	10.3	19.5	80.5	0.0
	45.0	16.5	76.9	6.61
Cs-134	3.0	8.74	91.3	0.0
	10.3	13.7	86.3	0.03
	45.0	1.04	69.4	29.5
	94.0	0.98	62.8	36.3
	967	0.23	58.8	41.0

TABLE VIII-10. TRANSFER FACTORS FROM FRESHWATER TO FISH OBSERVED IN NATURE

Species	Transfer factor (Bq/kg FM / Bq/L)	
	Sr-90	Cs-137
Silver carp	78 ± 38	300 ± 100
Bighead	—[a]	270 ± 90
Loach (*Memacheilus barbatulus*)	—	74 ± 29

[a] —: data not available.

TABLE VIII-11. TIME-DEPENDENT TF DATA OF CS-134 (FM BASIS) FROM FRESHWATER TO FISH

Day	Fish species						Note
	Tilapia (*Oreochromis nilotica*)			Common carp (*Cyprinus carpio*)			
	20 g	30 g	40 g	10 g	15 g	20 g	
7	11.9 ± 0.3	3.9 ± 0.8	7.8 ± 0.9	4.9 ± 1.1	5.5 ± 0.3	2.1 ± 1.1	Uptake
11	18.3 ± 0.8	14.2 ± 0.1	12.5 ± 0.1	8.9 ± 1.4	10.8 ± 0.7	7.7 ± 1.3	
16	24.1 ± 0.8	17.2 ± 0.2	16.2 ± 0.1	14.0 ± 1.8	14.0 ± 0.2	7.9 ± 0.6	
21	29.3 ± 0.7	18.3 ± 1.1	16.0 ± 1.0	18.2 ± 0.8	16.4 ± 0.3	14.1 ± 0.2	
25	37.5 ± 0.9	21.6 ± 0.3	19.7 ± 0.3	17.0 ± 2.4	18.6 ± 0.5	15.0 ± 0.5	
29	38.4 ± 0.4	21.5 ± 0.2	19.7 ± 0.1	20.5 ± 1.7	20.8 ± 0.2	18.0 ± 0.2	
33	40.1 ± 0.8	24.6 ± 0.6	18.8 ± 0.6	23.4 ± 0.5	21.7 ± 0.6	19.0 ± 0.3	
35	42.5 ± 0.3	24.8 ± 0.8	19.9 ± 1.3	23.8 ± 0.6	21.6 ± 0.4	17.6 ± 0.6	
38	35.1 ± 1.9	21.0 ± 1.4	16.1 ± 1.2	22.4 ± 0.9	18.6 ± 1.0	16.5 ± 0.1	Loss
41	29.6 ± 0.3	17.2 ± 0.5	12.0 ± 0.5	17.2 ± 0.7	15.5 ± 0.2	13.5 ± 0.4	

VIII-5.5. Impact of potassium and calcium content of crop on the transfer factor

It is well known that the potassium content of a crop has an impact on its caesium content, since these elements show similar behavior. The same applies to calcium and strontium. This correlation could not be ascertained during the experiment. Some data for TF of ^{134}Cs and potassium contents of crops are shown in Fig. VIII-6.

VIII-5.6. Freshwater to fish TF

Results of the experiments on the determination of freshwater to fish TF of ^{137}Cs, ^{90}Sr and ^{134}Cs are presented in Tables VIII-10 and VIII-11 and Fig. VIII-7.

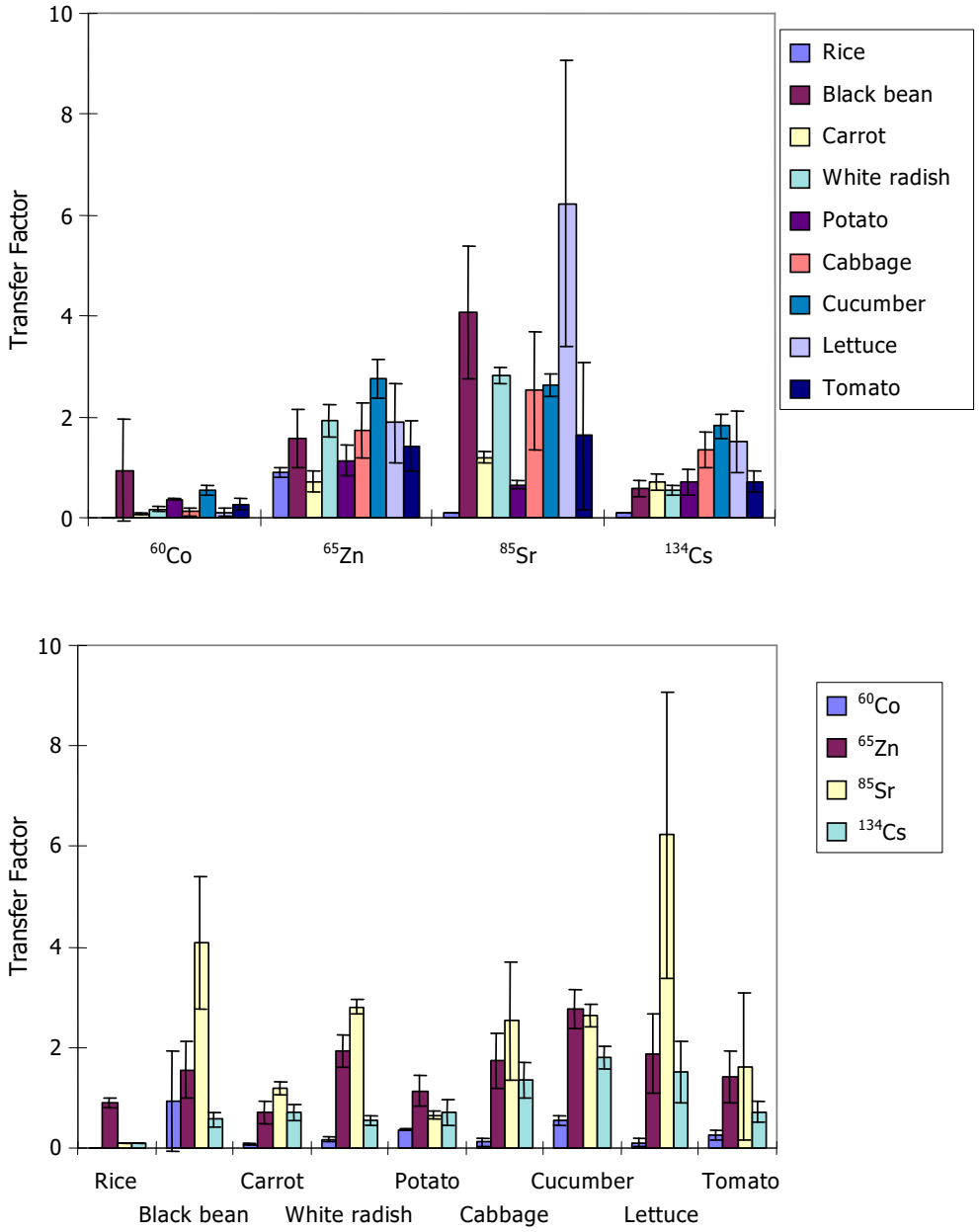

FIG. VIII-5. Average soil-to-plant TF derived from pot experiments (a: by radionuclide; b: by crop). Error bars represent standard deviation of the mean.

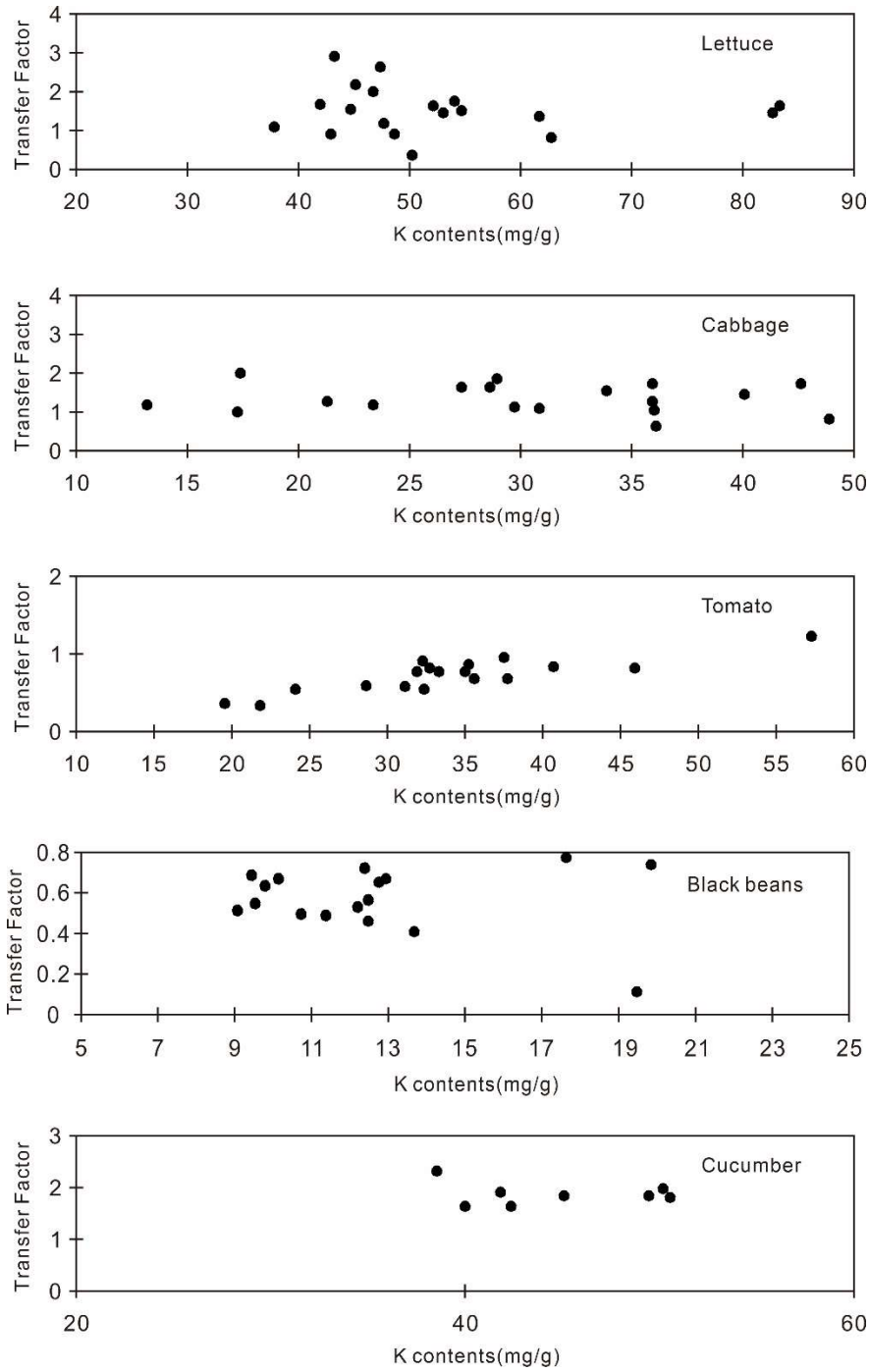

FIG. VIII-6. Relation between TF of ^{134}Cs and K contents of various crops.

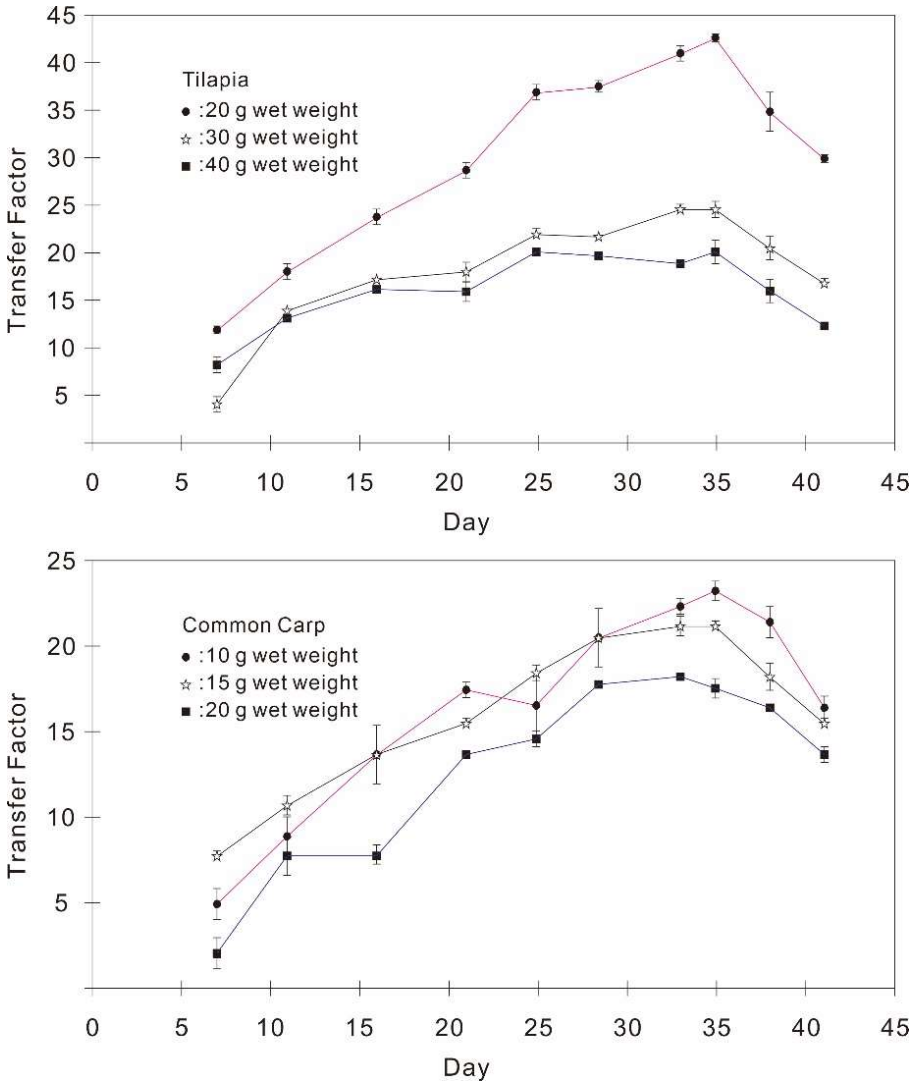

FIG. VIII-7. The TF of ^{134}Cs (FM basis) from freshwater to some fish species.

VIII-6. CONCLUSIONS

A comparison between soil-to-plant TF in temperate environment [VIII-1] and in the Vietnamese tropical environment shows that there are no systematic differences between data. The transfer parameters seem to depend on a large number of environmental variables, however, many of these variables could not yet be investigated; additional studies have to be carried out.

A comparison of freshwater to fish TF with data from other participants of the project shows that values are of the same order of magnitude. Also, in this case the impact of local conditions is high.

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ANNEX IX.

TRANSFER FACTORS OF ^{137}CS AND ^{90}SR FOR SELECTED CROPS IN SYRIA

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IX-1. INTRODUCTION

Radionuclides released during the Chernobyl accident in 1986, were detected in water, air, soil and vegetables throughout Syria [IX-1, IX-2]. The transfer of ^{137}Cs to foodstuffs was investigated for different kinds of crops but the data showed large variations [IX-3], which were attributed to variations in species, soil and weather conditions. This led the Syrian Atomic Energy Commission to establish a programme to investigate the behaviour of fission product radionuclides in typical soils of Syria and to study their transfer to some typical crops in the country. The programme started as part of a CRP with the IAEA. The aim of this project was to collect information about the TF of ^{137}Cs and ^{90}Sr from the soil to the major common crops in the country to use in models for the assessment of radiological risk in case of unexpected release of radionuclides.

IX-2. EXPERIMENTAL CONDITIONS

IX-2.1. Site selection

To assure the reproducibility of TF, a field study was carried out in this project. The field selected for the study was located in the agricultural station in the Syrian Atomic Energy Commission (about 30 km north east of Damascus), where about 2500 m^2 (50 m × 50 m) of land were isolated by a barrier and about 36m^2 (6 m × 6 m) in the center was homogeneously labelled with 1.85×10^8 Bq of ^{137}Cs and 3.7×10^8 Bq of ^{90}Sr.

IX-2.2. Soil conditioning and labelling

The experimental work started in 1994. The selected area was ploughed 4 times to ensure homogeneity, and all the stones were removed. The radionuclides were mixed and diluted to about 50 L with water after addition of 1 g of CsCl and 1 g of $SrCl_2$. The soil was labelled on 31 January 1994.

The radionuclide solution was spread on the area after saturation of the soil with water. A surface dosimeter was used to check the surface distribution homogeneity of the radionuclides. The soil was left to near dryness then ploughed using a cultivator to a depth of more than 25 cm seven times. Soil samples were then taken for analysis from five positions as shown in Fig. IX-1 (positions A to E); activity concentrations of ^{137}Cs were measured from 13 sampling points (see Fig. IX-1) to ensure the vertical and horizontal homogeneity.

IX-2.3. Seeding and growing

More than two months after labelling, the field was divided into different parts in accordance with the number of crops, which were planted as seeds in the field. The first seeding was carried out on 5 April 1994. Fertilizers were applied with irrigation water in accordance with current practices (see Tables IX-3 and IX-4).

Sorghum	5		13		4
Tomato	E	6		D 9	
Bean	10	A	1		12
Broad bean		7		8	
Chick peas	B 2		11	C	3
Melon					

FIG. IX-1. Sampling sites (A to E: Sampling position for soil analysis; 1 to 13: Sampling positions to assess homogeneity of radionuclide distribution).

IX-2.4. Radioactivity determination

Caesium-137 was determined using gamma spectrometry. About 80 g of dry powdered material (soil or dry crop) were sealed in a container and counted in a fixed calibrated geometry using a HPGe detector (active volume: 100 cm^3; relative efficiency: 15%). The amplified output of the detector was processed using a 4096 channel MCA system. Strontium-90 was extracted from ashed samples with HCl + HF and strontium was precipitated as nitrate with fuming nitric. After purification the final precipitate was counted directly after separation and after two weeks. Also, ^{85}Sr was used as a recovery determinant and in this case the ^{90}Y in equilibrium with ^{90}Sr was counted as β-radiation using a proportional counter [IX-4].

IX-2.5. Soil analysis

Electrical conductivity and pH were determined in 0.01 M $CaCl_2$ extracts with a soil solution ratio of 1:2.5 [IX-5]. Organic matter content was determined using the Tiurin's method where the organic material was oxidized with potassium dichromate and sulphuric acid; the extra dichromate was then calibrated using ferrous sulphate.

Soluble cations were determined by suitable chemical methods, where Mg^{++} and Ca^{++} were determined by titration with Na_2 EDTA at a pH of 12 and 10 respectively, while Na^+ and K^+ were determined using flame spectroscopy. To measure their exchangeable concentrations, alkali cations were extracted using ammonium acetate while earth alkali cations were exchanged with sodium chloride. The cationic exchange capacity was considered as the sum of the exchangeable cations.

Available phosphorous was determined by the Watanabe-Olsen method. The soil samples were washed with bicarbonate; the content of phosphorous was determined spectrophotometrically by measuring molybdenum blue at $\lambda = 320$ nm. Total pH phosphorous was determined by the Jackson method where the sample was digested with $HClO_4$ and the absorbance of phospho-ammonium molybdate measured at $\lambda = 420$ nm. Ammonium and nitrate were determined using distillation (Bremmer method). Trace elements were determined with atomic absorption techniques and X-ray fluorescence. Soil minerals were identified using X-ray diffraction techniques.

IX-3. RESULTS AND DISCUSSION

Table IX-1 reports the distribution of ^{137}Cs in the soil; it shows that a good homogeneity was achieved down to a depth of about 25 cm. Table IX-2 shows the soil properties, which reveals that the soil is a loamy clay and the organic matter is about 1%. The elemental and mineral composition of the soil are also given. The clay fraction is about 3% and consists of 40% kaolinite, 30% illite and 25% smectite.

The TF of ^{137}Cs and ^{90}Sr from the soil to the edible parts of some crops are shown in Tables IX-3 and IX-4 for 1994, 1995 and 1996 respectively. The results are generally comparable during these years except for chickpeas where the TF for both ^{137}Cs and ^{90}Sr were completely different for the first year compared to the next two years. These differences can be attributed to the difference of the growing seasons and the difference of the varieties, because in the first year a local variety was used, while in the following years the variety Gab-1 was sown. The reason is that the first crop was grown in summer, while the next crops were grown in winter.

The TF of ^{137}Cs and ^{90}Sr for cabbage varied significantly, even within one year; these variations might result from the differences in the ages of the leaves. The TF of ^{90}Sr were much higher than those of ^{137}Cs for all species, but the TF were always much higher for green parts.

TABLE IX-1. THE DISTRIBUTION OF CS-137 IN SOIL

Site No.	Activity concentration (Bq/kg)						
	0-5 cm	5-10 cm	10-15 cm	15-20 cm	20-25 cm	0-25 cm	Average [c]
1	6893	6422	6914	6165	5978	—	6474 ± 377
2	6251	6388	6239	8095	7856	—	6965 ± 829
3	8185	7454	7043	6487	6097	—	7051 ± 733
4	7676	6487	7142	6966	4289	—	6512 ± 1174
5	8220	7492	8190	8125	7875	—	7980 ± 272
6	—[a]	—	—	—	—	6132	n.a. [b]
7	—	—	—	—	—	6655	
8	—	—	—	—	—	6963	
9	—	—	—	—	—	8643	
10	—	—	—	—	—	7526	
11	—	—	—	—	—	7057	
12	—	—	—	—	—	8528	
13	—	—	—	—	—	8551	
Average [c]	7445 ± 10%	6849 ± 7%	7106 ± 9%	7168 ± 11%	6419 ± 20%	7507 ± 12%	7120 ± (7-13%)

[a] —: data not available.
[b] n.a. not applicable.
[c] Arithmetic Mean ± Standard Deviation (%).

TABLE IX-2. SOIL COMPOSITION FOR THE EXPERIMENTAL SYRIAN SOILS

Elemental composition		Mineral Composition	
Element	Value		Value
Ca	6.5 ± 0.5%	Quartz	60%
K	1.3 ± 0.2%	Calcite	32%
Na	0.4 ± 0.1%	Clay	3%
Sr	180 ± 10 ppm	Smectite	25%
Cs	3 ± 0.5 ppm	Kaolinite	40%
Fe	4 ± 0.2%	Illite	30%
Ti	0.5 ± 0.1%		
Mn	725 ± 70 ppm		
Cu	13 ± 3 ppm		
Zn	100 ± 10 ppm		
Rb	40 ± 4 ppm		
Y	20 ± 3 ppm		
Zr	209 ± 30 ppm		
Pb	10 ± 1 ppm		
As	10 ± 1 ppm		

TABLE IX-3. TRANSFER FACTORS OF CS-137 AND SR-90 TO THE EDIBLE PARTS OF CROPS (1995)

Crop	Seeding date	Part	Drying factor	Irrigation water (mm)	Fertilizer (kg/ha)			Transfer factor (individual value or range)	
					P_2O_5	K_2O	N	Cs-137	Sr-90
Chickpea	17 October 1994	Bean	0.4	550	20	80	—	0.002–0.003	0.1–0.27
Bean	19 March 1994	Pod	0.4–0.8	1300	150	100	30	0.02–0.07	0.2
Tomato	18 Apr 1994	Pod	0.05	2400	100	50	40	0.01–0.023	0.082–0.15
Watermelon	18 April 1994	Flesh	0.05	900	60	50	50	0.006–0.02	0.04–0.15
Cabbage	17 October 1994	Leaves	0.1	650	200	100	200	0.012–0.18	2.5–4.4
Broad bean	17 October 1994	Bean	0.8	700	100	100	30	0.008–0.011	0.08–0.13
		Pod	4					0.014–0.025	0.8–0.9
Sorghum	18 April 1994	Grain	0.92	700	90	60	60	0.003–0.004	0.021–0.048
		Straw						0.012–0.015	0.48–0.8
Garlic	13 November 1994	Cloves	—	7000	100	100	120	0.004 6	0.048
Onion	13 November 1994	Bulb	—	700	700	100	100	0.01–0.023	—
		Leaves						0.05–0.08	—
Wheat	22 November 1994	Grain	0.95	800	70	—	80	0.001–0.003	0.05
		Hay						0.01–0.02	—
Barley	15 November 1994	Grain	0.95	800	210	—	40	0.002–0.003	0.036
		Hay						0.012–0.02	0.24

a —: data not available.

TABLE IX-4 TRANSFER FACTORS OF Cs-137 AND Sr-90 TO SOME CROPS (1996)

Crop	Seeding date	Part	Drying factor	Irrigation water (mm)	Fertilizer (kg/ha)			Transfer factor (individual value or range)	
					P_2O_5	K_2O	N	Cs-137	Sr-90
Chickpea	31 October 1995	Grain	0.56–0.95	510	20	80	— [a]	0.003–0.006	0.14–0.28
Bean	25 April 1996	Bean	0.94	530	150	100	30	0.005–0.006	0.15–0.23
		Pod	0.91					0.018–0.02	1.6–2.5
Tomato	25 April 1996	Fruit	0.05	750	100	50	40	0.0015–0.028	0.23–0.37
Watermelon	25 April 1996	Flesh	0.05	650	60	50	50	0.0028–0.026	0.029–0.11
Cabbage	19 October 1995	Leaves	0.09–0.13	680	200	100	200	0.006–0.013	1.1–5
Broad bean	11 August 1995	Bean	0.92–0.93	660	100	100	30	0.005–0.006	0.095–0.17
		Pod	0.93					0.01–0.04	0.9–1.2
Garlic	31 October 1995	Cloves	0.25–0.26	660	100	100	120	0.0023–0.0033	0.066–0.081
Onion	11 December 1995	Bulbs	0.14	540	100	100	100	0.001–0.004	0.85–1.1
		Leaves	0.1–0.14					0.01–0.014	1.2–2.5
Sorghum	25 April 1996	Grain	0.92	650	90	60	60	0.0019–0.0033	0.017–0.25
		Hay	0.28					0.006–0.062	0.29–0.613
Wheat	11 August 1995	Grain	0.88–0.89	550	70	—	80	0.0011–0.0022	0.039–0.065
		Hay	0.87–0.9					0.0034–0.006	0.042–0.067
Barley	11 August 1995	Grain	0.89–0.92	475	210	—	40	0.0015–0.0016	0.063–0.065
		Hay	0.94					0.01–0.017	0.22–0.42

[a] —: data not available.

IX-4. ACKNOWLEDGEMENT

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ANNEX X.

TRANSFER FACTORS FOR FOODS GROWN ON BIKINI ISLAND AT BIKINI ATOLL

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X-1. INTRODUCTION

Bikini Atoll is located in the northern Marshall Islands, in the equatorial Pacific Ocean (11°35'N, 165°25'E). The atoll was one of the two sites in the Marshall Islands used by the Government of the United States of America to test nuclear devices. Between 1946 and 1958, a total of 23 devices were exploded at the atoll.

Since 1977, Lawrence Livermore National Laboratory has had an on-going field research project on Bikini Island to study the cycling and transport of radionuclides in the atoll ecosystem. As part of this effort, TF have been determined for ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am for the main food crops: coconuts, Pandanus, breadfruit, banana and papaya. A number of these plants were introduced in 1969 during a limited resettlement of Bikini Island. The TF for these tree crops is based on a soil depth of 40 cm that encompasses the active root zone, although the data presented in this report were calculated for a 20 cm depth as recommended by the protocol.

Corn, sorghum, squash, beans, cabbage and okra were planted in garden plots and sample collection started in 1985. The TF were determined from experimental control plots designed to evaluate remedial actions to reduce ^{137}Cs uptake. The TF were developed from soil cores taken to a depth of 20 cm. These annual food crops have a root zone that penetrates to a lesser depth than the tree crops.

X-2. DESCRIPTION OF STUDY SITE

Bikini Island is the largest landmass in the atoll and was the main residence island for the people of Bikini. This site was contaminated with radioactive fallout from a weapons test, code-named BRAVO, conducted on 1 March 1954 with an explosive yield of 15 MT.

The climate of the region is tropical with an average temperature of about 80°F (~27°C) and a mean annual rainfall of approximately 150 cm. There is a dry season between December and March, and a wet season between April and November.

The coral sand soil at Bikini Island, and other atolls in the Marshall Islands, is made up almost entirely of calcium carbonate ($CaCO_3$), with some $MgCO_3$ and essentially no silicate clay. This parent material is 25% corals, 35% Foraminifera, 15% Halimeda, 15% Lithothamnion, and 10% mollusk shells [X-1]. The carbonate matrix contains both the calcite and aragonite forms. These soils are low in exchangeable potassium ranging from 20 to 79 ppm in the top 25 cm. The highest concentrations are found in the top 5 cm layer as a result of both sea salt spray and decaying vegetation. There are marginal levels of phosphorous and trace metals in the soil. The pH ranges from 7.7 to 9.0, while the organic content of surface soils range from 2 to 14%. The organic matter decreases with depth in the soil column and is generally insignificant below about 40 cm depth. The soil median concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am as a function of depth in the soil column at Bikini Island are presented in Figure X-1.

Individual trees and their associated soils were randomly selected throughout the island. In addition, we determined TF from blocks of trees that became part of our radioecology/remedial measures experiments.

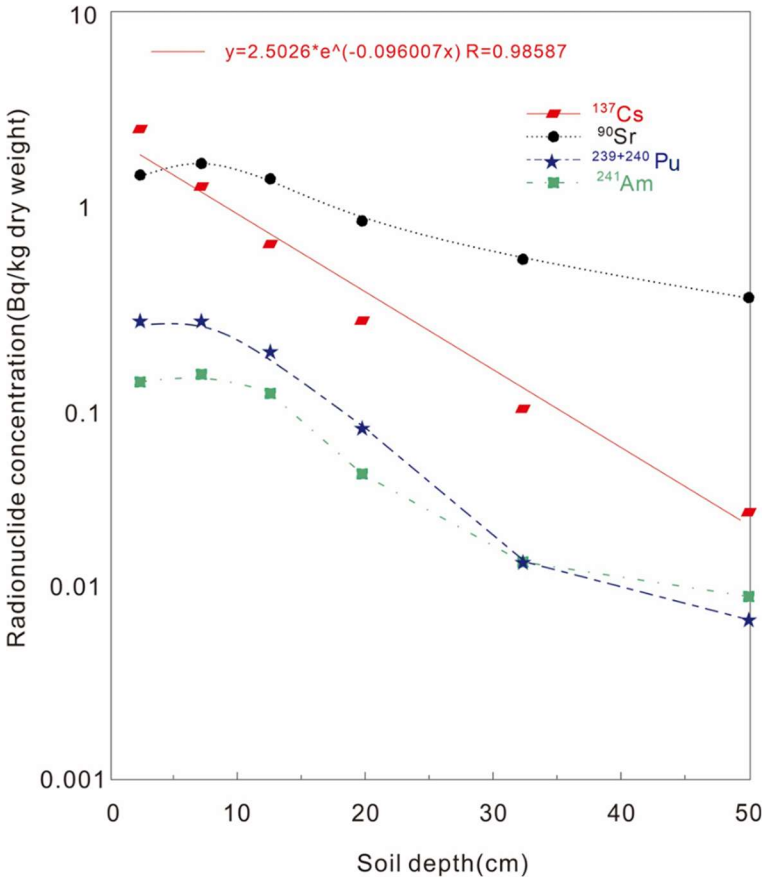

FIG. X-1. Median radionuclide concentrations in soil measured at Bikini Island.

X-3. FIELD PROCEDURES

Food crops and soils were collected during quarterly or semi-annual field trips to the atoll. All samples were frozen within 3 to 4 hours after collection and transported to the Lawrence Livermore National Laboratory for processing and radiological analysis. Detailed procedures can be found in Ref. [X-2].

Coconuts are the most common and abundant food crop on the island. A coconut sample consists of a composite of five to eight "drinking" or copra nuts depending on the majority of the type of nut present. The coconuts were husked, the fluid was collected in plastic bottles, and the intact shell containing the coconut meat was bagged and labelled.

Pandanus fruits are another food commonly consumed in the Marshall Islands. The fruits consist of numerous phalanges, or keys, attached to a central stalk. A bag of keys was taken in the field.

The annual food crops of breadfruit, papaya and banana were collected whole. A sample consists of approximately 5 to 10 fruits or vegetables resulting in a total mass of several kilograms. These food crops were generally taken when ripe, although there might be different levels of maturity for one crop (see Tables X-1 and X-2 for dry/fresh mass ratios).

Soil profiles for tree crops were taken in depth increments of 0-5, 5-10, 10-15, 15-25, 25-40, and 40-60 cm. A trench was dug radially from the trees to minimize root damage using a backhoe and a step method was used for sampling. Approximately two kilograms of soil were taken for each sample increment.

Soil cores associated with annual food crops were taken in the experimental plots to a depth of 20 cm. These plots were usually confined to a small area, and soil coring techniques were used to minimize the mixing of the existing soil column horizons that may result when using the trench profile method.

X-4. LABORATORY PROCESSING PROCEDURES

Samples were received frozen at the Lawrence Livermore National Laboratory, where they were inventoried and sent to the processing laboratories. In the laboratory the coconut meat was taken out of the shell, diced into small pieces and the shell was discarded. The coconut fluid was processed separately. The other food crop samples were washed to remove any soil, dissected into different segments (meat, skin and seeds if available) and weighed. The samples were then freeze-dried, reweighed and ground to a homogenous texture. Soil samples were dried and sterilized, sieved through a 1 mm screen, and ball-milled to produce a homogenous sample. The homogenized plant and soil samples were pressed into an aluminium can or vial, with volumes of 222 cm^3 and 42 cm^3, respectively. The detailed procedures can be found in Stuart [X-2] and Stoker and Conrado [X-3].

X-5. ANALYTICAL PROCEDURES

After the samples were processed, non-destructive assays of ^{137}Cs and other gamma emitting radionuclides were performed at the Low-Level Gamma Spectroscopy Facility (LLGSF) of LLNL.

After gamma analysis was completed, a number of samples were analyzed for ^{90}Sr, $^{239+240}Pu$ and ^{241}Am. The analysis was carried out either at the LLNL radiochemistry laboratory or by an outside contractor. Wet chemistry analysis at LLNL was performed by standard methodology [X-6].

Both the LLGSF and the LLNL radiochemistry laboratory have their own internal Quality Control Programmes [X-4], which include a series of standards, duplicates, spikes and blanks. The Quality Control Programme for the Marshall Islands also includes intercomparison exercises, interlaboratory comparisons and split-samples analyses. Results from our MI QC program are summarized in [X-5] and [X-7]. Data produced by the analyses are not released unless they pass the Quality Control requirements described in [X-5]

X-6. RESULTS AND DISCUSSION

The TF from Bikini Island for ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am are summarized in Tables X-1 to X-5; the radionuclide concentration in crops and moisture content are also included. All data were decay corrected to 1 January 1996.

Each individual tree (major food crop) with its associated soil was sampled numerous times through the years. The results were averaged to produce a single TF. A mean TF was then calculated from all trees sampled. The garden plot crops with their associated soil were sampled once and a TF calculated. A mean TF was averaged from each individual crop location.

The TF for ^{137}Cs and ^{90}Sr determined on Bikini Island are much different than those found in temperate environments. In temperate zones values range from 0.005 to 0.53 for caesium and 0.02 to 3.0 for strontium [X-8]. The TF for coral soils at Bikini Island range from about 0.4 to about 40 for ^{137}Cs and from about 0.003 to about 0.2 for ^{90}Sr (see Tables X-1 to X-3). The data therefore indicate that the uptake of caesium is higher than strontium in coral soils, which is the opposite of what is observed in continental silica-based soils.

The TF of ^{137}Cs in breadfruit, banana, corn and squash (0.4 to 4) appear to be lower than those found in coconuts, Pandanus, papaya and sorghum (6 to 20), whereas the highest value was observed for Chinese cabbage (40). The TF of ^{90}Sr for coconuts range between 0.003 and 0.01, while TF for Pandanus, breadfruit and papaya are of the order between 0.1 and 0.5 (see Table X-3).

The TF of plutonium and americium in the tropical environment are very similar to those in temperate ecosystems. The TF in temperate zones range from 8.6×10^{-6} to 4.4×10^{-3} for plutonium and 2.2×10^{-5} to 2.2×10^{-3} for americium [X-8], while TF for $^{239+240}Pu$ and ^{241}Am observed in Bikini Island range from 1×10^{-6} to 1×10^{-4}.

Because of the unique features of the coral soil on Bikini Island, ^{137}Cs is mobile in the carbonate-organic complex and relatively available to plants, whereas ^{90}Sr is bound in the carbonate matrix and is relatively unavailable to plants and $^{239+240}Pu$ and ^{241}Am are essentially unavailable to plants.

TABLE X-1. SOIL-TO-PLANT TRANSFER FACTORS AND ACTIVITY CONCENTRATIONS OF CS-137 IN FOOD CROPS GROWN ON BIKINI ISLAND[a]

	No. of trees	No. of samples	Median	Arithmetic mean	Standard deviation	Minimum	Maximum	Confidence limit	
								Lower 95%	Upper 95%
				Drinking coconut (meat)					
Transfer factor			6.3	8.2	6.1	1.4	32	2.0	26
Activity concentration (kBq/kg DM [b])	106	448	14	14	8.6	0.88	59	2.7	32
DM to FM [b] ratio			0.29	0.29	0.070	0.090	0.45		
				Copra (meat)					
Transfer factor			5.5	6.9	4.9	2.1	28	2.4	17
Activity concentration (kBq/kg DM)	55	128	12	12	4.9	1.4	32	2.9	21
DM to FM ratio			0.58	0.58	0.060	0.45	0.80		
				Pandanus					
Transfer factor			17	21	14	5.5	41	—[c]	—
Activity concentration (kBq/kg DM)	9	39	20	18	12	3.6	34	—	—
DM to FM ratio			0.19	0.19	0.060	0.090	0.35		
				Breadfruit (meat)					
Transfer factor			1.4	1.7	1.2	0.22	3.7	—	—
Activity concentration (kBq/kg DM)	8	35	2.2	2.3	1.2	0.86	4.7	—	—
DM to FM ratio			0.25	0.22	0.070	0.11	0.32		
				Papaya (meat)					
Transfer factor			5.4	11	10	1.0	31	—	—
Activity concentration (kBq/kg DM)	23	49	20	28	27	1.0	110	—	—
DM to FM ratio			0.11	0.11	0.030	0.070	0.19		
				Banana (meat)					
Transfer factor			0.39	0.36	0.17	0.13	0.60	—	—
Activity concentration (kBq/kg DM)	5	5	0.49	0.67	0.38	0.33	1.1	—	—
DM to FM ratio			0.28	0.28	0.030	0.25	0.31		

[a] Transfer factors were calculated for a 20 cm depth as IUR protocol, but the data were collected to a depth of 40 cm, which includes the root zone of the trees. TFs calculated based on 20 cm depth are half those based on 40 cm depth. Activity concentrations are decay corrected to 1996.
[b] DM: Dry Mass; FM: Fresh Mass.
[c] —: data not available.

TABLE X-2. SOIL-TO-PLANT TRANSFER FACTORS AND ACTIVITY CONCENTRATIONS OF CS-137 FOR FOOD CROPS GROWN ON BIKINI ISLAND[a]

	No. of samples	Median	Arithmetic mean	Standard deviation	Minimum	Maximum	Confidence limit Lower 95%	Confidence limit Upper 95%
			Sorghum (whole)					
Transfer factor		8.1	10	6.6	0.81	24	1.6	24
Activity concentration (kBq/kg DM [b])	55	26	26	13	3.6	51	4.6	49
DM to FM [b] ratio		0.30	0.30	0.080	0.12	0.53		
			Sorghum (seed heads)					
Transfer factor		11	13	8.2	0.94	31	—	—
Activity concentration (kBq/kg DM)	15	21	24	14	1.5	55	—	—
DM to FM ratio		0.74	0.63	0.21	0.33	0.84		
			Corn (kernels)					
Transfer factor		0.88	1.4	1.4	0.20	7.8	0.25	3.9
Activity concentration (kBq/kg DM)	41	1.9	2.8	2.8	0.31	14	0.31	10
DM to FM ratio		0.31	0.35	0.13	0.14	0.58		
			Corn (stalks)					
Transfer factor		2.3	2.5	1.8	0.49	9.0	0.60	6.7
Activity concentration (kBq/kg DM)	27	3.9	4.8	3.3	1.0	16	1.0	13
DM to FM ratio		0.18	0.18	0.043	0.12	0.31		
			Chinese cabbage (leaf)					
Transfer factor		36	41	37	2.9	144	— [c]	—
Activity concentration (kBq/kg DM)	17	45	50	31	2.4	115	—	—
DM to FM ratio		0.075	0.077	0.019	0.036	0.11		
			Squash					
Transfer factor		2.7	3.6	2.7	0.73	9.7	—	—
Activity concentration (kBq/kg DM)	10	2.3	3.0	2.3	0.62	8.2	—	—
DM to FM ratio		0.099	0.12	0.057	0.064	0.23		
			Sweet potato					
Transfer factor		3.5	3.0	1.1	1.7	3.8	—	—
Activity concentration (kBq/kg DM)	3	6.2	4.8	2.9	1.5	6.8	—	—
DM to FM ratio		0.34	0.31	0.059	0.25	0.36		
			Yard Long Beans					
Transfer factor		3.9	n.a.[c]	n.a.	n.a.	n.a.	n.a.	n.a.
Activity concentration (kBq/kg DM)	1	3.3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
DM to FM ratio		0.26						
			Okra					
Transfer factor		1.9	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Activity concentration (kBq/kg DM)	1	1.6	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
DM to FM ratio		0.120						

[a] Transfer factors are calculated from kBq/kg fruit DM versus 0-20 cm kBq/kg soil DM. Activity concentrations are decay corrected to 1996.
[b] DM: Dry Mass; FM: Fresh Mass.
[c] —: data not available; n.a.: Not applicable.

TABLE X-3. SOIL-TO-PLANT TRANSFER FACTORS AND ACTIVITY CONCENTRATIONS OF SR-90 FOR FOOD CROPS GROWN ON BIKINI ISLAND[a]

	No. of trees	No. of samples	Median	Arithmetic mean	Standard deviation	Minimum	Maximum	Confidence limit	
								Lower 95%	Upper 95%
			Drinking coconut meat						
Transfer factor			0.008 9	0.011	0.008 2	0.001 9	0.037	0.003 4	0.036
Activity concentration (kBq/kg DM [b])	30	48	0.023	0.024	0.016	0.0015	0.092	0.004 5	0.058
DM to FM [b] ratio			0.30	0.30	0.070	0.16	0.45		
			Copra meat						
Transfer factor			0.002 8	0.0037	0.003 9	0.000 60	0.015	—[c]	—
Activity concentration (kBq/kg DM)	16	28	0.004 8	0.0063	0.007 7	0.001 1	0.028	—	—
DM to FM ratio			0.61	0.61	0.063	0.52	0.72		
			Pandanus						
Transfer factor			0.53	0.48	0.26	0.13	0.83	—	—
Activity concentration (kBq/kg DM)	5	6	0.58	1.1	1.1	0.17	3.0	—	—
DM to FM ratio			0.23	0.21	0.054	0.13	0.25		
			Breadfruit meat						
Transfer factor			0.13	0.13	0.11	0.018	0.29	—	—
Activity concentration (kBq/kg DM)	7	11	0.22	0.28	0.28	0.021	0.85	—	—
DM to FM ratio			0.25	0.26	0.029	0.21	0.31		
			Papaya meat						
Transfer factor			0.19	0.26	0.15	0.11	0.44	—	—
Activity concentration (kBq/kg DM)	5	5	0.52	0.72	0.53	0.12	1.4	—	—
DM to FM ratio			0.070	0.076	0.022	0.050	0.11		

[a] Transfer factors are calculated from kBq/kg fruit DM versus 0-20 cm kBq/kg soil DM. Activity concentrations are decay corrected to 1996.
[b] DM: Dry Mass; FM: Fresh Mass.
[c] —: data not available.

TABLE X-4. SOIL-TO-PLANT TRANSFER FACTORS AND ACTIVITY CONCENTRATIONS OF PU-239+240 FOR FOOD CROPS GROWN ON BIKINI ISLAND[a]

	No. of trees	Median	Arithmetic mean	Standard deviation	Minimum	Maximum	Confidence limit	
							Lower 95%	Upper 95%
			Drinking coconut (meat)					
Transfer factor	16	2.8×10^{-5}	3.2×10^{-5}	2.4×10^{-5}	4.9×10^{-6}	9.5×10^{-5}	—[c]	—
Activity concentration (kBq/kg DM[b])	16	6.1×10^{-6}	9.6×10^{-6}	1.3×10^{-5}	9.5×10^{-7}	5.4×10^{-5}	—	—
DM to FM[b] ratio	16	0.28	0.29	0.020	0.26	0.34		
			Copra (meat)					
Transfer factor	13	5.0×10^{-6}	1.6×10^{-5}	2.2×10^{-5}	2.2×10^{-7}	7.3×10^{-5}	—	—
Activity concentration (kBq/kg DM)	13	1.4×10^{-6}	2.8×10^{-6}	2.6×10^{-6}	2.5×10^{-7}	9.3×10^{-6}	—	—
DM to FM ratio	13	0.59	0.59	0.030	0.55	0.66		
			Pandanus					
Transfer factor	2	6.7×10^{-5}	6.7×10^{-5}	1.9×10^{-5}	5.4×10^{-5}	8.1×10^{-5}	—	—
Activity concentration (kBq/kg DM)	2	2.5×10^{-5}	2.5×10^{-5}	2.2×10^{-5}	9.1×10^{-6}	4.0×10^{-5}	—	—
DM to FM ratio	2	0.16	0.16	0.035	0.13	0.18		
			Breadfruit (meat)					
Transfer factor	6	3.3×10^{-5}	2.9×10^{-5}	2.0×10^{-5}	5.2×10^{-6}	5.6×10^{-5}	—	—
Activity concentration (kBq/kg DM)	6	5.7×10^{-6}	7.0×10^{-6}	4.5×10^{-6}	1.9×10^{-6}	1.3×10^{-5}	—	—
DM to FM ratio	6	0.25	0.24	0.017	0.21	0.25		
			Papaya (meat)					
Transfer factor	3	1.5×10^{-6}	1.7×10^{-5}	2.7×10^{-5}	6.3×10^{-7}	4.8×10^{-5}	—	—
Activity concentration (kBq/kg DM)	3	1.2×10^{-6}	3.5×10^{-5}	6.0×10^{-5}	9.0×10^{-7}	1.0×10^{-4}	—	—
DM to FM ratio	3	0.070	0.077	0.031	0.050	0.11		

[a] Transfer factors were calculated for a 20 cm depth as IUR protocol, but the data were collected to a depth of 40 cm, which includes the root zone of the trees. TFs calculated based on 20 cm depth are half those based on 40 cm depth. Activity concentrations are decay corrected to 1996.
[b] DM: Dry Mass; FM: Fresh Mass.
[c] —: data not available.

TABLE X-5. SOIL-TO-PLANT TRANSFER FACTORS AND ACTIVITY CONCENTRATIONS OF AM-241 FOR FOOD CROPS GROWN ON BIKINI ISLAND[a]

	No. of trees	Median	Arithmetic mean	Standard deviation	Minimum	Maximum	Confidence limit	
							Lower 95%	Upper 95%
			Drinking coconut (meat)					
Transfer factor		2.0×10^{-5}	3.7×10^{-5}	4.9×10^{-5}	6.9×10^{-6}	1.4×10^{-4}	—[c]	—
Activity concentration (kBq/kg DM [b])	7	5.9×10^{-6}	4.4×10^{-6}	4.5×10^{-6}	1.9×10^{-6}	1.3×10^{-5}	—	—
DM to FM [b] ratio		0.29	0.29	0.029	0.26	0.34		
			Copra (meat)					
Transfer factor		7.9×10^{-6}	2.6×10^{-5}	5.0×10^{-5}	1.6×10^{-6}	1.7×10^{-4}	—	—
Activity concentration (kBq/kg DM)	11	1.5×10^{-6}	1.9×10^{-6}	1.4×10^{-6}	4.0×10^{-7}	4.4×10^{-6}	—	—
DM to FM ratio		0.59	0.59	0.028	0.56	0.66		
			Breadfruit (meat)					
Transfer factor		3.3×10^{-5}	4.8×10^{-5}	5.1×10^{-5}	7.8×10^{-6}	1.2×10^{-4}	—	—
Activity concentration (kBq/kg DM)	4	3.4×10^{-6}	4.2×10^{-6}	3.4×10^{-6}	1.1×10^{-6}	9.0×10^{-6}	—	—
DM to FM ratio		0.24	0.24	0.019	0.21	0.25		
			Papaya (meat)					
Transfer factor		1.1×10^{-5}	1.1×10^{-5}	8.6×10^{-6}	5.0×10^{-6}	1.7×10^{-5}	—	—
Activity concentration (kBq/kg DM)	2	6.4×10^{-6}	6.4×10^{-6}	6.9×10^{-6}	1.5×10^{-6}	1.1×10^{-5}	—	—
DM to FM ratio		0.080	0.080	0.042	0.050	0.11		

[a] Transfer factors were calculated for a 20 cm depth as IUR protocol, but the data were collected to a depth of 40 cm, which includes the root zone of the trees. TFs calculated based on 20 cm depth are half those based on 40 cm depth. Activity concentrations are decay corrected to 1996.
[b] DM: Dry Mass; FM: Fresh Mass.
[c] —: data not available.

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ANNEX XI.

TRANSFER FACTORS OF 137CS AND 85SR FOR FRESHWATER FISH IN TROPICAL ENVIRONMENTS IN THAILAND

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XI-1. INTRODUCTION

A pre-operational assessment is legally required by national authorities for nuclear facilities to demonstrate that the consequence of planned discharges of radioactive effluents are in compliance with the established dose limits. In general, models are employed to predict the transport of radionuclides within ecosystems and potential doses to humans. It has long been recognized that radionuclide transfer parameters are very important for an accurate application of such models. The values of transfer parameters have been compiled for a wide range of elements and radionuclides of concern for routine releases from nuclear facilities including those currently published by the IAEA. However, in these compilations, parameters for tropical environments, such as those typical of Thailand, are few and therefore the procurement of new data has been encouraged throughout tropical regions. In addition to this, there is also a concern for applying default values in assessment models where resulting doses are close to the pertaining dose limit [XI-1].

This experiment was focused on the derivation of TF in edible fish in freshwater ecosystems of ^{137}Cs and ^{85}Sr, which are the main contributors to the dose received by the local population.

XI-2. MATERIALS AND METHOD

XI-2.1. Fish species

The mixed breed catfish between Thai catfish *Clarias acrocephalus* and African sharptooth catfish *Clarias garispinus* is a good representative of tropical fish under controlled laboratory condition and thus was recommended by the expert from the fishery department for this experiment. Besides, its comparatively low cost and good flavor has led to popularity among consumers.

XI-2.2. Acclimatization

Live fish were purchased from the market. Fish with a length of 25–33 cm and a mass of 160-270 g were selected and were immersed in radionuclide-free tap water for 30 days before experimental exposure in 1000 L tanks filled with 500 L of tap water. During this time, fish were fed daily using commercial fish food at 0.3% fish weight. Fifty-six percent of fish survived at the end of the acclimatization period. The density of the experimental tanks was less than 10 g fish/L.

XI-2.3. Experimental design

Three experiments were conducted, all with the same basic apparatus. Experiment 1 used relatively high concentrations of ^{137}Cs only, and the uptake with time by soft and bone tissues was recorded. This simple experiment confirmed the appropriateness of our method. Experiment 2 included ^{137}Cs at about a tenfold lower concentration as well as ^{85}Sr. Uptake by

the whole fish was recorded as a function of time. Experiment 3 was the most complex one, both ^{137}Cs and ^{85}Sr were included and uptake by four different tissues was recorded.

XI-2.4. Radionuclides

A standard solution of ^{137}Cs was obtained commercially from Amersham, while ^{85}Sr was obtained by neutron activation reaction using $SrCl_2$ as a target material in a 2 MW, TRIGA MARK III research reactor with neutron flux of 3×10^{12} n/cm^2/s. Prior to the exposure period, ^{137}Cs and ^{85}Sr were introduced into the accumulation tanks using the same quality and quantity of water as those for acclimatization and loss period. A continuous flow of water was maintained until homogeneity was achieved. An aliquot of 100 g of contaminated pond sediment exposed to effluents from the research reactor was also included in the water. The activities in the tanks were counted each day until steady state was achieved; the measured activity concentration of ^{137}Cs in Experiment 1 was 249 kBq/L, while the activity concentrations of ^{137}Cs and ^{85}Sr in Experiment 2 were 28 and 1 kBq/L respectively and in Experiment 3, ^{137}Cs and ^{85}Sr activity concentrations were 63 and 3.1 kBq/L respectively. Commercial fish food was delivered at the same rate as given during acclimation,

XI-2.5. Distribution coefficients (K_d)

The distribution coefficient or K_d is the ratio of the radioactivity of the radionuclide adsorbed on the solid phase or sediment to the radioactivity of the radionuclide remaining in solution:

$$K_d(\mathrm{L/kg}) = \frac{\text{Amount of radionuclide absorbed on sediment}}{\text{Amount of radionuclide remaining in solution}} \quad \text{(XI-1)}$$

K_ds of fish food and contaminated sediment were measured. The results for fish food were 2.9 and 15 L/kg for ^{137}Cs and ^{85}Sr respectively, (ratio 1:10, shaking at 150 rpm for one day). The K_d values for contaminated sediment were 351 and 22 L/kg for ^{137}Cs and ^{85}Sr respectively (ratio 1:10, shaking at 150 rpm for 7 days).

XI-2.6. Analysis of samples

Two fish were withdrawn at regular intervals of time over a period of 47 days and were rinsed with tap water. At the same time, 100 ml water samples were collected and filtered using a 0.45 µm membrane filter. Fish were dissected into flesh plus skin and bone in Experiment 1, and into flesh, skin, bone and head in experiment 3. Afterwards fish parts were oven-dried at 100°C for 1 day and subsequently ashed at 430°C for another day prior to analysis of both ^{137}Cs and ^{85}Sr by gamma-ray spectrometry. In experiment 2, the whole fish bodies were counted alive.

The counting system consists of a Hyperpure Germanium Detector connected to an 8092 multichannel analyzer. A mixed standard solution obtained from NPL, England (originating from Amersham) was employed for efficiency calibrations. All values obtained were corrected for radioactive decay to the first day of the uptake experiment and expressed in Bq/kg, fresh mass (FM) basis. Chemical analyses of calcium and potassium in filtered water were performed by 'Direct Calibration' using a calcium electrode, model 93-20, Orion, and a potassium electrode, model 93-19, Orion, USA respectively. Dissolved oxygen of the water was measured with a portable Aquamerk kit, Germany, and pH was measured with a pH electrode, Orion, USA.

XI-2.7. Analysis of experimental data

The observed uptake data appeared to approach an equilibrium value and could be fit using a model with exponential equations of the form:

$$Q(t) = Q_{eq}(1 - e^{-\lambda t}) \quad \text{(XI-2)}$$

where Q(t) is the activity in fish in Bq/kg FM at time t; Q_{eq} is the activity in fish in Bq/kg FM at equilibrium and λ is the rate coefficient given by the equation:

$$T_{1/2} = \frac{0.693}{\lambda} \quad \text{(XI-3)}$$

where $T_{1/2}$ is the biological half-life. Q_{eq} can be expressed as:

$$Q_{eq} = TF \; x \; C \quad \text{(XI-4)}$$

TF is the concentration factor at equilibrium in L/kg and C is the activity concentration in water at steady state in Bq/L.

The statistical package Sigmastat (Jandel Scientific Software, Version 1.0: 1994) using an iterative Marquardt-Levenberg algorithm was applied to determine the parameters of Eq. (XI-1) above [XI-2].

XI-3. RESULTS AND DISCUSSION

The physical and chemical parameters of filtered water are shown in Table XI-1. Calcium and potassium were also analyzed because they are the nutrient analogs of ^{85}Sr and ^{137}Cs respectively. The concentration of both radionuclides in fish depends on the level of their nutrient analogs in the water compartment. Since the concentration of the two elements in freshwater ecosystems are very dependent on the site, TF for the two radionuclides will have no real meaning values unless their nutrient analogues are reported.

Results of three experimental aquarium studies on uptake of ^{137}Cs and ^{85}Sr by mixed blood Thai-African Cat fish (Figs. XI-1–XI-3) suggest that the exponential models as in Eq (XI-1) are applicable. Table XI-2 shows results of all key parameters in the model.

The TF for ^{137}Cs in flesh plus skin and bone determined in Experiment 1 were 4.3 and 3 L/kg respectively. The corresponding biological half-lives calculated from Eq. (XI-2) were 29 and 18 days respectively. The TF of ^{137}Cs and ^{85}Sr for the whole fish determined in experiment 2 were 1.8 and 4.9 L/kg respectively. The biological half-lives for ^{137}Cs and ^{85}Sr were 36 and 39 days respectively. Experiment 3 was designed to demonstrate the effect of fish parts on uptake of both radionuclides. The highest TF of ^{137}Cs in fish parts was determined for flesh (3.2 L/kg), followed, in decreasing order, by that for bone (2.6 L/kg), skin plus fin (1.6 L/kg) and head (1.5 L/kg). The corresponding half-lives calculated from Eq. (XI-3) were 41, 40, 42 and 33 days respectively. As far as the accumulation of ^{85}Sr in fish parts is concerned, the highest TF was calculated for the head (17.2 L/kg), followed by, in decreasing order, that for the bone (4.03 L/kg), skin plus fin (0.99 L/kg) and flesh (0.11 L/kg). The corresponding half-lives were 37, 11.8, 3.9 and 4.0 days.

TABLE XI-1. PHYSICAL AND CHEMICAL PARAMETERS OF WATER USED IN THE EXPERIMENTS

Parameter	Experiment 1	Experiment 2	Experiment 3
pH	7.0 ± 0.9	8.4 ± 0.4	8.0 ± 0.5
Temperature (°C)	27.0 ± 1.5	26.5 ± 0.8	29.6 ± 0.8
Dissolved oxygen	7.7 ± 1.1	8.5 ± 0.9	9.3 ± 1.8
Potassium (mg/L)	29.0 ± 5.5	12.6 ± 2.9	22.2 ± 1.2
Calcium (mg/L)	67.0 ± 4.2	42.4 ± 6.1	64.0 ± 2.4

TABLE XI-2. VALUES OF PARAMETERS FITTED TO THE UPTAKE MODEL (EQ. XI-1)

Experiment	Parameter	Value							
1		Cs-137							
		Flesh + Skin				Bone			
	TF (L/kg)	4.3				3.0			
	$T_{1/2}$ (d)	29				18			
2		Cs-137				Sr-85			
		Whole fish body				Whole fish body			
	TF (L/kg)	1.8				4.9			
	$T_{1/2}$ (d)	36				39			
3		Cs-137				Sr-85			
		Skin	Flesh	Bone	Head	Skin	Flesh	Bone	Head
	TF (L/kg)	1.6	3.2	2.6	1.5	0.99	0.11	4.03	17.2
	$T_{1/2}$ (d)	42	41	40	33	4	3.9	11.8	37

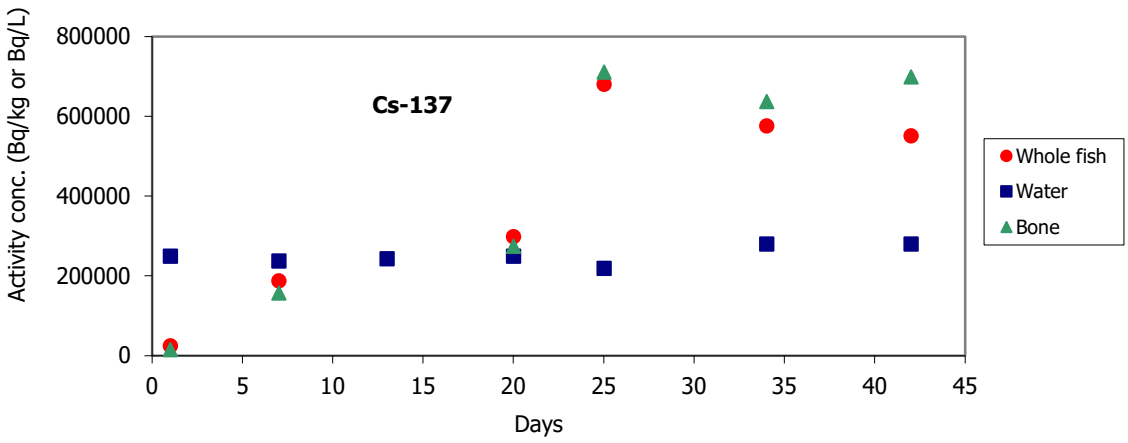


FIG. XI-1. Activity concentrations of ^{137}Cs (Bq/kg, FM) measured in water, flesh plus skin and bone as a function of time of exposure in Experiment 1.

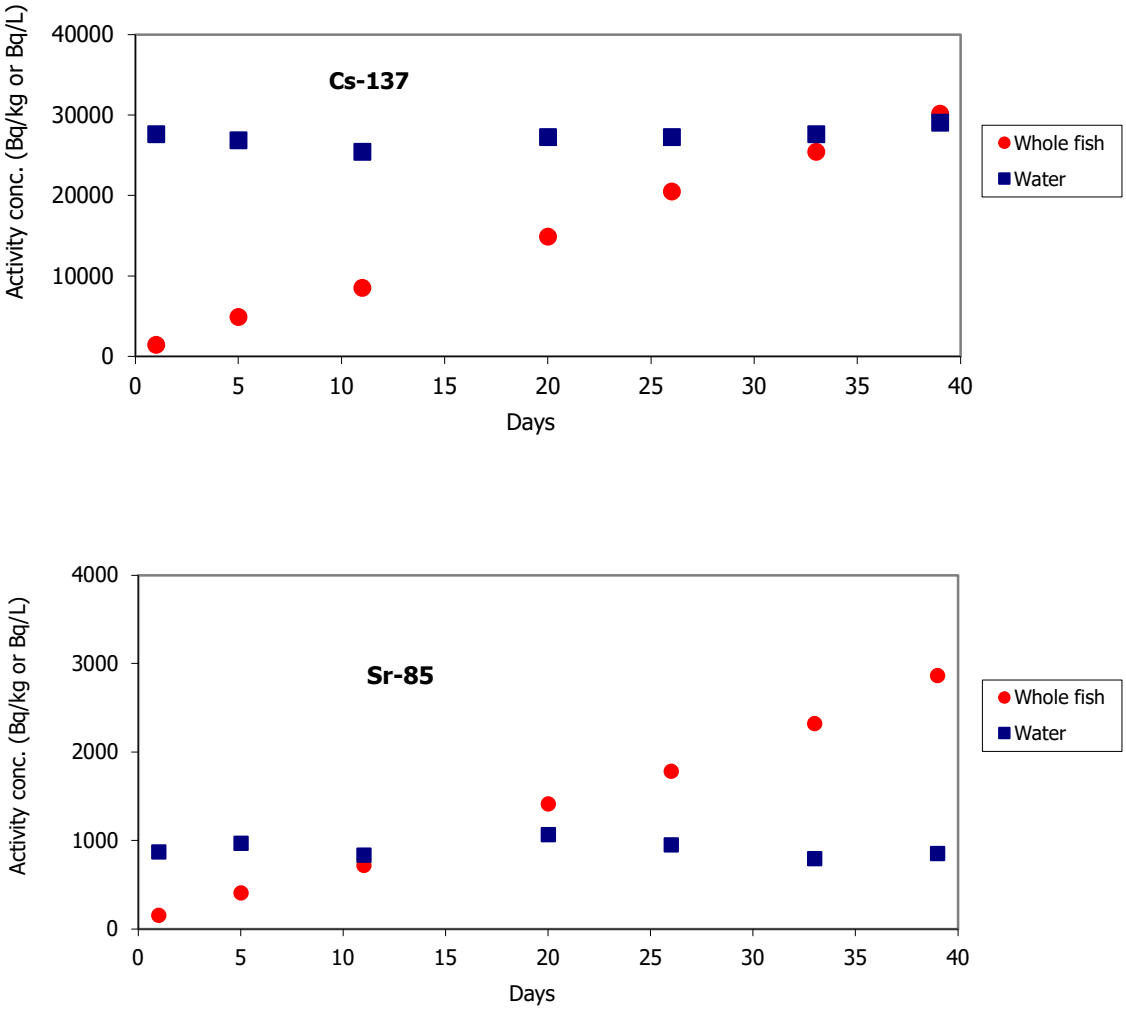
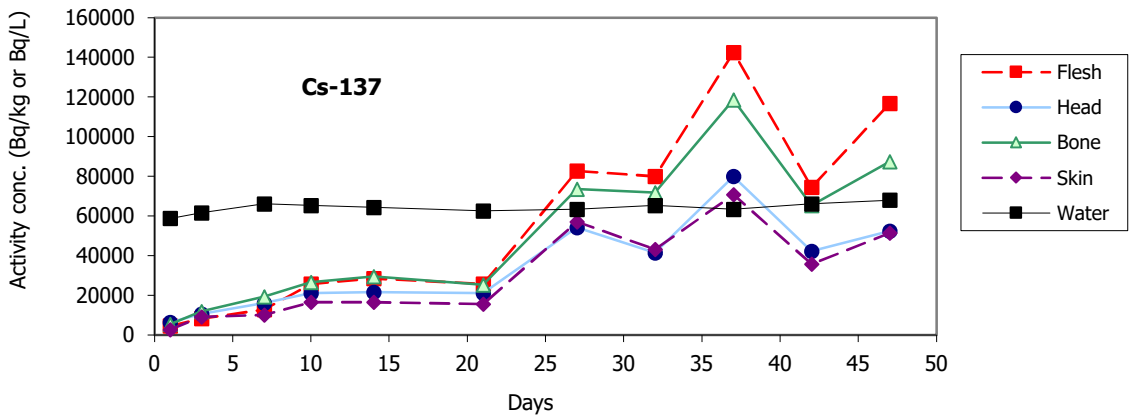
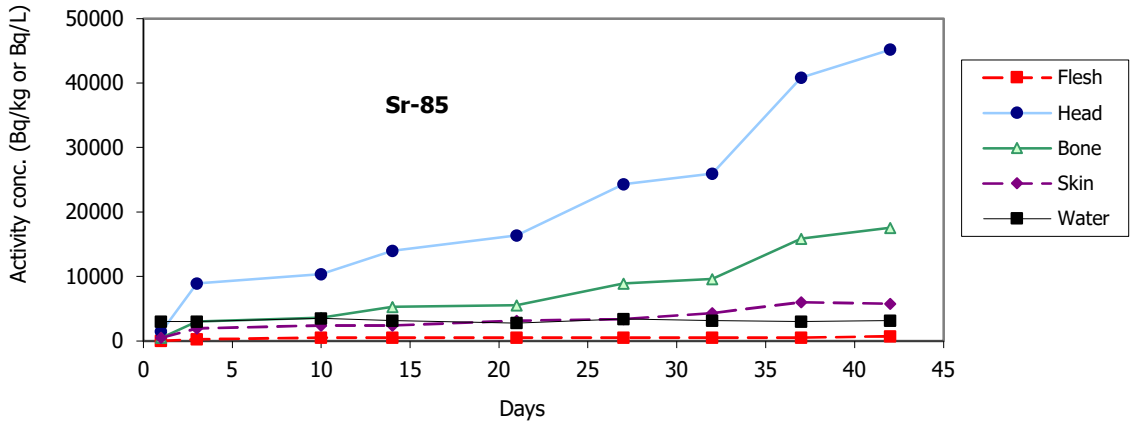


FIG. XI-2. Activity concentrations of ^{137}Cs and ^{85}Sr (Bq/kg, FM) measured in water and whole fish as a function of time of exposure in Experiment 2.



(a)



(b)

FIG. XI-3. Activity concentrations of ^{137}Cs (a) and ^{85}Sr (b) (Bq/kg, FM) measured in water and fish components as a function of time of exposure in Experiment 3.

Fig. XI-4 shows the percentage distribution of ^{137}Cs and ^{85}Sr in fish parts. The percentages in each fish part were calculated by dividing the activity of the radionuclide in that particular part by the total activity in whole fish body except viscera. The arithmetic means and standard deviations (averaged over time) on a FM basis for ^{137}Cs were 56 ± 7% in the flesh, 25 ± 6% in the head, 13 ± 3% in the bones and 7 ± 1% in the skin plus fin. For ^{85}Sr the values were: 78.6 ± 3.9% in the head 12.5 ± 1.0% in the bone, 4.6 ± 0.8% in the skin plus fin and 4.3 ± 3.1% in the flesh.

The remarkably high percentage of ^{85}Sr measured in the head is worth considering in dose estimates for individuals who consume freshwater fish as a prime source of meat and include the whole fish in the meal. The highest accumulation of ^{137}Cs was in flesh tissue, as was observed by other investigators in the CRP. It is also quite important to note that more than half of the remaining radioactivity accumulated in the head, as the head is also an edible part used in Thai cuisine.

The mean percentage of ash contents of the various fish components are shown in Table XI-3. The results were in good agreement with reported values elsewhere. Calcium and potassium were also analyzed in fish components and are shown in Table XI-3.

The results of laboratory studies on the uptake of radionuclide revealed much lower numerical values than those reported elsewhere [XI-3–XI-4], especially for ^{137}Cs. The differences between the values reported here and elsewhere can be attributed to differences in environmental conditions, such as different feeding regime, but in particular to the termination of exposure prior to achieving equilibrium. Because our experiment only lasted 47 days, estimated biological half-lives longer than 30 days must be interpreted with caution and a longer experiment would be required to confirm these half-lives. To calculate doses to the public from a release of radioactive liquid waste to freshwater ecosystems, this variability of environmental conditions should be recognized and taken into account. To validate such an assessment, site-specific investigations to derive key parameter values at that particular site may be necessary.

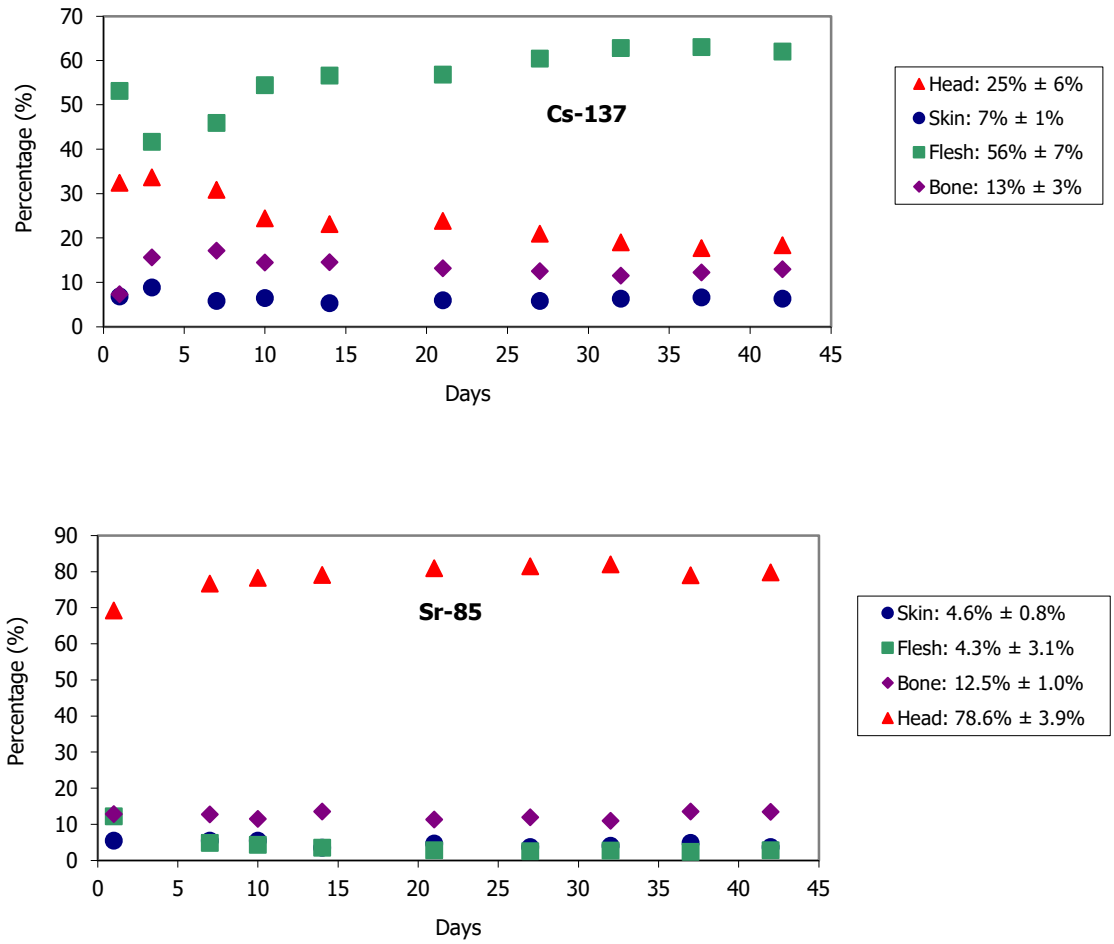


FIG. XI-4. Percentage distribution of ^{137}Cs and ^{85}Sr measured in some tissues of fish in experiment 3. The mean and standard deviations, averaged versus time, are indicated.

TABLE XI-3. PERCENTAGE ASH AND CALCIUM AND POTASSIUM CONCENTRATIONS IN VARIOUS FISH PARTS (MG/100 G, FM [a])

Fish part	Ash (% of FM)	Concentration (mg/100 g, FM)	
		Ca	K
Skin + fin	2.15 ± 0.22	8.5 ± 1.5	4.3 ± 1.1
Flesh	1.24 ± 0.10	1.2 ± 0.5	11.5 ± 1.9
Bone	6.34 ± 0.31	9.1 ± 1.5	2.3 ± 0.3
Head	14.20 ± 0.47	11.4 ± 2.1	1.1 ± 0.1

[a] FM: Fresh Mass.

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ANNEX XII.

TRANSFER FACTORS OF ^{134}CS FOR OLIVE AND ORANGE TREES IN GREECE

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XII-1. OBJECTIVES

The objective of this research programme was mainly to determine TF of ^{134}Cs from soil to tree crops (olive and orange trees) in a long-term glasshouse pot experiment, started in 1994. The influence of the soil characteristics on ^{134}Cs uptake was also studied by selecting two soils which had different physical and chemical properties.

XII-2. EXPERIMENTAL SET UP

XII-2.1. Crop types

Two tree crops, which are of major importance for the economy of Greece, were selected for this experiment: olive trees (*Olea Europaea*) and orange trees (*Citrus sinensis*). For olive trees the local variety "Koroneiki" was used which is a broadly cultivated variety for olive oil production. From citrus trees the orange variety "Navel New Hall" was selected as these oranges constitute 84% of the cultivated citrus species in Greece.

XII-2.2. Soil types

The two selected soils were representative and suitable for the crops included in the study, but they differed in their characteristics as shown in Table XII-1. The first soil was calcareous, heavy textured, the second was an acid-light textured soil.

XII-2.3. Pots

The experiment was conducted in large pots (lower diameter 70 cm, upper diameter 85 cm, depth 50 cm) containing 110 kg of soil where olive and orange trees two years after grafting were transplanted. Four replications for the first soil and three for the second were used.

XII-2.4. Soil labelling

Soil labelling was performed in February and April 1994, respectively, for both soils. The same technique to label the soil with ^{134}Cs as that applied in previous experiments with annual crops was essentially followed, because it was considered successful. An activity of 1.85×10^7 Bq of ^{134}Cs as CsCl was added to each pot. The soil was added to each pot in 22 layers of 2 cm thickness (5 kg of soil). On the top of each layer 500 ml of the CsCl solution was added in the form of very small drops. The soil in the pots was watered to field capacity and left to stand for eight weeks for the ^{134}Cs to reach equilibrium and then transplanting followed. To make transplanting of the trees easy and safe an empty pot of the same size as the one in which the trees were grown, was put into the large pots and set at the desired height.

Plant samples were taken when the fruit had matured in November 1994, October 1995 and November 1996. Generally accepted methods were used for chemical analyses, while soil and plant samples were counted for ^{134}Cs in a complete gamma-spectroscopy setup.

TABLE XII-1. CHARACTERISTICS OF SOILS USED IN THE TREE EXPERIMENT

	Texture (%)			pH	CEC (meq/100 g)	Exchangeable K (meq/100g)	Organic matter (%)
	Sand	Silt	Clay				
Soil 1	8.2	51.4	46.4	7.5	18.2	0.68	2.8
Soil 2	57.2	29.4	13.4	5.6	5.6	0.22	1.1

XII-3. RESULTS AND DISCUSSION

Activity concentrations of ^{134}Cs in orange and olive trees measured between November 1994 and November 1996 are presented in Tables XII-2 and XII-3. Both evergreen tree crops showed similar behavior in the soils included in the study. The ability of both tree species to absorb ^{134}Cs from the roots seems to be significantly influenced by the soil type. The activity concentration in both tree species grown on calcareous and heavy soil was very low and did not change much with the time. On the contrary, trees grown on acid and light soil showed much higher ^{134}Cs concentration (up to 32 times for orange and 21 for olive trees) which increased with time. By the third year of growth activity concentrations of ^{134}Cs in the olive trees seemed to reach an equilibrium with no further increase, while those in the orange trees kept increasing.

The new parts of both crops showed higher ^{134}Cs concentration than the old ones up to the second year of experimentation but a more uniform distribution of ^{134}Cs was observed by the third year especially in the olive trees. The highest ^{134}Cs concentration was observed in the edible parts of the oranges.

Although significant activity concentrations of ^{134}Cs were measured in olives grown on acid soils, no ^{134}Cs was detected in the unprocessed olive oil. This may be due to the water solubility of ^{134}Cs compounds and their removal during the separation of olive oil.

The results of this study are in agreement with similar trends in the uptake of ^{134}Cs and ^{85}Sr in annual crops grown under comparable conditions. The TF of ^{134}Cs for the trees investigated were of the same range of magnitude as values of annual crops grown under similar conditions. The TF showed a great variability with the soil type and were inversely correlated with pH and exchangeable calcium and manganese or exchangeable bases [XII-1–XII-3].

The TF of ^{134}Cs determined in these investigation (Tables XII-4 and XII-5) showed similar trends to the activity concentrations of ^{134}Cs measured. The TF of ^{134}Cs were very low in the calcareous-heavy soil and much higher in the acid-light soil. The largest difference was observed in the edible part of the orange, for which the ratio of the highest to the lowest value was 43. The differences in uptake of ^{134}Cs by trees depend on many factors and it was not investigated in detail. Data regarding the influence of micro-organisms on ^{134}Cs availability, although contradictory, do not exclude that soil fungi to play an important role in the ^{134}Cs uptake from acid-organic soils [XII-4].

The TF are probably higher than those which may be obtained from undisturbed soil since the pots used in the experiment were more or less uniformly labelled while in field studies 95% of radiocaesium is within the top 10 of the soil profile where few roots are present [XII-5]. Root uptake does not seem to be a major mechanism for absorption of ^{134}Cs in calcareous soils, although it can be significant in acid soils. No differences in potassium content of the trees grown on either calcareous or acid soil were noticed. Potassium content did not also change with time. No correlation was found between the potassium content of plant parts and TF of ^{134}Cs.

TABLE XII-2. ACTIVITY CONCENTRATIONS OF CS-134 IN ORANGE TREES

Date	Activity concentration (Bq/kg, DM) [a]				
	New leaves	Old leaves	New branches	Edible fruit	Skin
		Calcareous Heavy Soil			
November 1994	220	185	132	146	ND [b]
October 1995	296	244	331	299	276
November 1996	337	433	523	552	493
		Acid Light Soil			
November 1994	1 903	ND	1 961	ND	ND
October 1995	7 173	3 075	4 849	ND	ND
November 1996	8 714	9 245	8 248	16 763	11 969

[a] Values are corrected for radioactive decay (Reference date: November 1994); DM: dry mass.

[b] ND: Not detected.

TABLE XII-3. ACTIVITY CONCENTRATIONS OF CS-134 IN OLIVE PLANTS

Date	Activity concentration (Bq/kg, DM) [a]					
	New leaves	Old leaves	New branches	Old branches	Fruit	Olive oil
			Calcareous Heavy Soil			
November 1994	342	152	263	116	177	ND [b]
October 1995	324	131	202	220	314	ND
November 1996	339	426	399	275	512	ND
			Acid-Light Soil			
November 1994	1909	797	1607	724	455	ND
October 1995	5908	2102	4224	2654	3819	ND
November 1996	3816	3697	3696	2226	3708	ND

[a] Values are corrected for radioactive decay (Reference date: November 1994); DM: dry mass.

[b] ND: Not detected.

TABLE XII-4. TRANSFER FACTORS OF CS-134 FOR ORANGE TREES

Date	Transfer factor				
	New leaves	Old leaves	New branches	Edible fruit	Skin
		Calcareous Heavy-Soil			
November 1994	0.001	0.000 9	0.000 6	0.007	n.a. [a]
October 1995	0.001 4	0.001 1	0.001 5	0.001 4	0.001 3
November 1996	0.000 6	0.001 9	0.002 4	0.002 6	0.002 3
		Acid-Light Soil			
November 1994	0.013	n.a.	0.014	n.a.	n.a.
October 1995	0.047	0.020	0.032	n.a.	n.a.
November 1996	0.058	0.061	0.054	0.11	0.079

[b] n.a.: Not applicable.

TABLE XII-5. TRANSFER FACTORS OF CS-134 FOR OLIVE TREES

Date	Transfer factor				
	New leaves	Old leaves	New branches	Old branches	Fruit
		Calcareous Heavy-Soil			
November 1994	0.002	0.0009	0.001 6	0.000 8	0.001 1
October 1995	0.002	0.0008	0.001 2	0.001 3	0.002 2
November 1996	0.001 9	0.0024	0.002 4	0.001 7	0.002 9
		Acid-Light Soil			
November 1994	0.013	0.005 2	0.011	0.004 8	0.003
October 1995	0.039	0.014	0.028	0.018	0.025
November 1996	0.025	0.024	0.024	0.015	0.024

XII-4. CONCLUSIONS

The TF of ^{134}Cs for orange and olive trees depended on soil type. They were low in the calcareous-heavy soil and higher in the acid-light soil (difference of up to 43 times). The TF of ^{134}Cs for the studied trees were of the same order of magnitude as those of annual crops grown under similar conditions. Although a significant amount of ^{134}Cs was measured in olives of trees grown on acid soil no ^{134}Cs was detected in the olive oil. Root uptake of ^{134}Cs is not an important mechanism for ^{134}Cs contamination of evergreen trees grown on calcareous soil; however, it might be significant in acid soils.

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ANNEX XIII.

TRANSFER FACTORS OF ^{137}CS FROM SOIL TO TEA AND THYME LEAVES IN TURKEY

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XIII-1. OBJECTIVES

The objectives of the investigations were:

(1) To determine the TF of ^{137}Cs in tea leaves from Chernobyl contaminated soil and soil labelled with artificial radionuclides in an experimental nursery area of Rize town in the eastern Black Sea region of Turkey;
(2) To determine the TF of ^{137}Cs and ^{134}Cs in thyme leaves from Chernobyl contaminated soil and soil labelled with artificial radionuclides in pot and field experiments, respectively;
(3) To determine the TF of ^{137}Cs in grapefruit, mandarin, wild strawberry, olive leaves and kiwi fruit from Chernobyl contaminated soils;
(4) To determine the TF of ^{134}Cs for tomatoes, peppers, parsley, purslane, black cabbage, sunflower, pumpkin, lettuce and corn samples from soil labelled with artificial radionuclides in a field experiment; and
(5) To determine properties of soil samples and tea leaves.

XIII-2. EXPERIMENTAL APPROACH

XIII-2.1. Tea experiment

In Turkey, tea is cultivated along the eastern coast of the Black Sea, especially in the town of Rize. Tea grown in Turkey is a small-leafed China hybrid type known as *Camellia sinensis var. Sinensis*. The entirely dentate tea leaves remain green and do not fall for several years. The usual size of the leaves ranges from 3.8 to 6.4 cm in length and from 1.2 to 2 cm width [XIII-1]. Tea plant leaves are harvested from newly formed fresh leaves two to three times a year in May–June, July–August and September.

The experimental plantation area was prepared in the nursery area of Rize in December 1993 using soils with high and low activity concentrations of radionuclide of Chernobyl origin. The soil containing high activity concentrations of Chernobyl fallout (mean activity concentration of ^{137}Cs: 1400 ± 12 Bq/kg, dry mass (DM)) was scraped from the surface layer and transported to the plantation area. Thirty-two holes of 40 cm in diameter and 60 cm in depth were excavated in the plantation. The soil containing high activity concentrations of Chernobyl fallout was divided into two parts: (1) one part was transferred directly into 12 holes, and (2) the other part was further treated by adding ^{137}Cs (~52 MBq/m^3) before being transferred to 8 holes. At the same time, the soil containing low activity concentrations of Chernobyl fallout (mean activity concentration of ^{137}Cs: 19 ± 5 Bq/kg, DM) was transferred to 12 holes for control purpose. Young tea plants from an area not labelled with ^{137}Cs were uprooted during April 1994 by agriculturists and planted into the prepared holes in the nursery area. Fifty grams of NPK fertilizer were added to each tea plant group in March, every year.

XIII-2.2. Thyme experiment

In Anatolia, several types of thyme are cultivated: *Thymus*, *Origanum*, *Coridathymus*, *Thymbra* and *Satureja*, all of which are used as seasoning and in medicine. For the determination of TF of radiocaesium in thyme plants, specimens of *Origanum vulgare* ssp. were uprooted from a natural growing area in west Anatolia in April 1995 [XIII-2]. The specimens were divided into two parts after being transported to the laboratory. After the adaptation period, eight thyme plants were planted in the pots which were filled with Chernobyl contaminated soil (mean ^{137}Cs 308 ± 8 Bq/kg DM). The other thyme plants were planted in the field of the Çekmece Nuclear Research and Training Center (ÇNAEM). The soil type was representative of the thyme cultivating area. This soil was also further treated with the addition of ^{134}Cs (mean ^{134}Cs concentration: 63 400 ± 540 Bq/kg DM).

All pots were irrigated with water at ambient conditions. Growth conditions were 14 hours at 25°C during daytime and 10 hours at 20°C during the night. The plants in the field experiment were irrigated with water twice weekly if there was no rain. No fertilizer or insecticides were applied in either the pot or the field experiments.

XIII-2.3. Additional studies

Additional samples of grapefruit, mandarin, wild strawberry, olive leaves and kiwi fruit were collected from an orange garden beside the nursery tea experimental area in Rize town during 1995–1996. Plants of tomato, pepper, purslane and black cabbage were also planted and parsley and corn were sown in the fields of ÇNAEM, the soil of which contains artificial radioactivity.

XIII-2.4. Chemical analysis

The soil was characterized using standard analytical methods [XIII-3]. The content of potassium in crops was determined by Instrumental Neutron Activation Analysis (INAA) or the tetraphenylborate method using a DR/2000 Hach spectrophotometer. Other procedures were similar to those described in the protocol of the CRP (see Annex II above). INAA analysis was applied for the element analyses of soil and tea leaves samples. About 0.2 g of the samples and standards (IAEA's CRM Soil-5 and NBS's SRM Estuarine Sediment 1646) were put into polyethylene tubes and irradiated for INAA. Irradiations were carried out for 2 hours at a thermal neutron flux of about 2×10^{13} ncm^{2}s in TR-2 Reactor. After allowing for radioactive decay for periods of 24 hours for short-lived radionuclides and 3 to 4 weeks for long-lived radionuclides, gamma spectra were measured for 2000 and 80 000 seconds, respectively.

XIII-2.4.1. Radionuclides and counting techniques

The procedures to label the soils, sampling and calculation of TF are described in the General Protocol for TF determination (see Annex II above). Activities of ^{137}Cs and ^{134}Cs were determined using a gamma-ray spectrometry system based on an HPGe detector with a resolution (FWHM) of 1.8 keV at 1332.5 keV (^{60}Co). The energy calibration was performed using a solid mixed gamma reference source from Amersham. All samples were counted for 50 000 seconds.

XIII-3. RESULTS

XIII-3.1. Transfer factors of ^{137}Cs in tea leaves

Values for TF are given in Table XIII-1. The data were divided into four groups according to the type of soil and the radiocaesium activity concentrations. Soil type 'a' contained high activity concentrations of radiocaesium of Chernobyl origin and was further divided into two subgroups: a_1 indicates the soil containing only high activity concentrations of radiocaesium of Chernobyl origin, while a_2 indicates the soil containing only high activity concentrations of radiocaesium of Chernobyl origin to which additional ^{137}Cs was added. Soil type 'b' contained high activity concentration of radiocaesium of Chernobyl origin and soil type 'c' contained low activity concentrations of caesium of Chernobyl origin. The TF of ^{137}Cs for tea leaves were lower in soil a_1 than in a_2. These differences in the TF are also clearly shown in Fig. XIII-1, where TF are presented as a function of time on a log-normal scale. The mean TF for soils of types b and c were 0.19 and 0.75 respectively. The TF of ^{137}Cs were in the leaves grown over type c soil than those grown over type b soil. The properties of the soils are given in Table XIII-2.

XIII-3.2. Transfer factors of ^{137}Cs of Chernobyl origin in other crops from garden

The TF of ^{137}Cs in crops collected from the orange garden in Rize are given in Table XIII-1; properties of the garden soil are shown in Table XIII-2. The data showed differences in the TF for different species. The highest TF was observed for mandarin fruit, followed by, in decreasing order, grapefruit juice, kiwi fruit, wild strawberry and olive leaves.

XIII-3.3. Transfer factors of radiocaesium radionuclides in thyme leaves

Table XIII-3 shows the TF of ^{137}Cs and ^{134}Cs of Chernobyl origin in thyme leaves determined in pot and field experiments. The lowest TF values were found in the field experiment. The TF were lower in winter than in summer under field conditions. The properties of the soils used in pot and field experiments are given in Table XIII-4.

XIII-3.4. Transfer factors of ^{134}Cs for field conditions

The TF for ^{134}Cs in leaf vegetables (purslane, parsley, black cabbage and lettuce) were in the range of 0.008 to 0.102. The TF for fruits of tomato, pumpkin and pepper were 0.004, 0.002 and 0.017, respectively. In addition, TF were calculated for some components of sunflower and corn plants. The TF of sunflower seeds and corncob were lower than those for sunflower cake and cornstalk. All results and properties of the soil are given in Tables XIII-3 and XIII-4.

XIII-3.5. Element analysis

The concentrations of stable elements in tea leaves and soil samples are given in Table XIII-5. Higher content of iron, cobalt, zinc and potassium are observed in fresh tea leaves, while calcium and barium concentrations are higher in old tea leaves. Concentrations of nickel, cobalt, caesium, chromium, barium, arsenic and sodium in soil taken from the field of Çekmece Nuclear Research Centre were relatively high. Also, the concentrations of bromine, selenium and thorium of the highly contaminated Chernobyl soil were relatively high. The other elements were distributed quite uniformly in all soil types.

TABLE XIII-1 TRANSFER FACTORS OF CS-137 FOR TEA LEAVES AND OTHER CROPS

Soil type [1]	Crop, part	Planting date	Chemical form	Activity Concentration (Bq/kg)	Date of labelling	Date of harvest	Root depth (cm)	K in crop (%)	Dry matter (%)	Transfer factor
a_1	Tea 1 flush leaves	April 1994	— [2]	566	May 1986	May 1994	15	1.00	23	0.056
a_2	Tea 1 flush leaves	April 1994	Cl	5050	March 1994	June 1994	15	1.01	25	0.046
b	Tea 2 flush leaves	Old plant	—	602	May 1986	June 1994	30	1.07	25	0.35
b	Tea 2 flush leaves	Old plant	—	602	May 1986	June 1994	30	1.07	24	0.14
b	Tea 2 flush leaves	Old plant	—	602	May 1986	June 1994	30	1.07	23	0.079
c	Tea 3 flush leaves	Old plant	—	19	May 1986	August 1994	30	0.99	25	0.89
c	Tea 3 flush leaves	Old plant	—	19	May 1986	August 1994	30	0.99	23	0.63
c	Tea 3 flush leaves	Old plant	—	19	May 1986	August 1994	30	0.99	21	0.63
a_1	Tea 1 flush leaves	April 1994	—	630	May 1986	May 1995	13	2.50	24	0.051
a_2	Tea 1 flush leaves	April 1994	Cl	6940	March 1994	May 1995	13	2.18	25	0.16
a_1	Tea 2 flush leaves	April 1994	—	664	May 1986	August 1995	15	2.21	23	0.087
a_2	Tea 2 flush leaves	April 1994	Cl	7508	March 1994	August 1995	15	2.00	42	0.19
a_1	Tea 1 flush leaves	April 1994	—	1170	May 1986	June 1996	18	1.21	24	0.066
a_2	Tea 1 flush leaves	April 1994	Cl	6607	March 1994	June 1996	18	1.21	25	0.17
a_1	Tea 3 flush leaves	April 1994	—	1510	May 1986	September 1996	18	0.95	23	0.086
a_2	Tea 3 flush leaves	April 1994	Cl	8650	March 1994	September 1996	18	0.95	24	0.17
d	Grapefruit juice	Old plant	—	339	May 1986	May 1996	30	—	6.5	0.032
d	Grapefruit dre.	Old plant	—	339	May 1986	May 1995	30	3.07	12.6	0.006
d	Mandarin fruit	Old plant	—	339	May 1986	May 1995	30	1.25	6.9	0.035
d	Mandarin skin	Old plant	—	339	May 1986	May 1995	30	1.52	24.6	0.009
d	Wild strawberry	Old plant	—	339	May 1986	May 1995	8	—	—	0.006
d	Olive leaves	Old plant	—	330	May 1986	03/1996	—	—	33	n.a. [3]
d	Kiwi fruit	1988	—	322	May 1986	12/1996	6	1.34	—	0.026

[1] The following codes are used to describe the soil types (soil properties are described in Table XIII-2 below):

a_1: high-level Chernobyl contaminated soil;
a_2: high-level Chernobyl contaminated soil (a_1) which was also contaminated by additional ^{137}Cs;
b: Chernobyl contaminated soil of tea plantation area;
c: low-level Chernobyl contaminated soil;
d: Chernobyl contaminated soil of orange garden.

[2] —: Data not available.

[3] n.a.: Not applicable.

TABLE XIII-2. PROPERTIES OF SOIL IN RIZE TOWN

Date	Soil type [1]	Composition (%)			pH (CaCl2)	Organic matter (%)	C org. (%)	T. salt (%)	Exchangeable K (meq/100 g)	CEC (meq/100 g)	Exchangeable K (%)
		Sand	Silt	Clay							
May 1994	a	40	37	23	6.00	4.35	2.52	0.07	1.12	16.6	6.76
May 1994	b	26	27	47	4.30	5.22	3.03	0.05	0.340	9.3	4.26
May 1994	c	23	31	46	3.90	2.40	1.39	0.06	0.93	13.8	6.71
May 1995	a	37	28	35	4.10	5.22	1.83	0.20	0.87	25.6	2.45
August 1995	a	39	33	28	4.90	4.85	2.70	0.08	1.03	33.5	4.40
May 1995	d	25	28	47	4.40	5.30	2.96	0.04	0.41	9.3	4.10
June 1995	a	38	36	26	5.30	4.60	3.10	0.09	1.23	— [2]	—

[1] The following codes are used to describe the soil types:
a: high-level Chernobyl contaminated soil (type a_1 and a_2); b: Chernobyl contaminated soil of tea plantation area; c: low-level Chernobyl contaminated soil; d: Chernobyl contaminated soil of orange garden.
[2] —: Data not available.

TABLE XIII-3. TRANSFER FACTORS OF RADIOCAESIUM IN THYME LEAVES AND OTHER CROPS

Soil type [1]	Crop, part	Planting date	Chemical form	Activity Concentration (Bq/kg)	Date of labelling	Date of harvest	Root depth (cm)	K in crop (%)	Dry matter (%)	Transfer factor
a	Thyme, leaves	May 1995	— [2]	338	May 1986	October 1995	8	2.1	36	0.21
a	Thyme, leaves	May 1995	—	357	May 1986	July 1996	8	2.1	28	0.31
b	Thyme, leaves	October 1995	Cl	12 774	May 1995	July 1996	8	1.9	25	0.15
b	Thyme, leaves	October 1995	Cl	16 020	May 1995	October 1996	8	2.2	30	0.12
b	Thyme, leaves	October 1995	Cl	13 285	May 1995	March 1997	9	2.1	20	0.061
b	Tomato, fruit	August 1995	Cl	45 925	May 1995	October 1995	14	4.1	6	0.004
b	Pepper fruit	August 1995	Cl	45 925	May 1995	October 1995	12	4.4	12	0.017
b	Parsley	August 1995	Cl	45 925	May 1995	October 1995	10	6.1	12	0.024
b	Purslane	August 1995	Cl	45 925	May 1995	October 1995	8	3.7	14	0.11
b	Sunflower, grain	—	Cl	45 925	May 1995	October 1995	15	—	—	0.000 3
b	Sunflower, cake	—	Cl	49 925	May 1995	October 1995	15	—	—	0.003
b	Blake cabbage	August 1995	Cl	49 925	May 1995	October 1995	13	2.5	17	0.008
b	Pumpkin	May 1996	Cl	44 554	May 1995	November 1995	15	3.6	—	0.002
b	Lettuce	May 1996	Cl	44 554	May 1995	November 1995	10	—	—	0.013
b	Cornstalk	May 1996	Cl	34 144	May 1995	October 1996	25	—	—	0.008
b	Corncob	May 1996	Cl	34 144	May 1995	October 1996	25	—	—	0.002

[1] The following codes are used to describe the soil types:
a: high-level Chernobyl contaminated soil (type a_1 and a_2); b: Chernobyl contaminated soil of tea plantation area; c: low-level Chernobyl contaminated soil; d: Chernobyl contaminated soil of orange garden.
[2] —: Data not available.

TABLE XIII-4. PROPERTIES OF POT AND FIELD SOILS

Date	Soil type [1]	Composition (%)			pH (CaCl2)	Organic matter (%)	C org. (%)	T. salt (%)	Exc. K (meq/100 g)	CEC (meq/100 g)	Exc. K (%)
		Sand	Silt	Clay							
May 1995	a	60	17	23	4.30	5.48	3.06	0.06	1.07	35.7	1.90
July 1996	a	63	16	21	4.90	3.80	— [2]	—	0.90	—	1.70
May 1995	b	7	52	45	7.20	1.83	—	0.10	0.55	38.8	1.43
October 1996	b	11	45	44	7.10	2.10	—	—	0.51	—	—

[1] The following codes are used to describe the soil types:
a: high-level Chernobyl contaminated soil (type a_1 and a_2); b: Chernobyl contaminated soil of tea plantation area;
[2] —: Data not available.

TABLE XIII-5. ELEMENTAL ANALYSIS OF TEA LEAVES AND SOIL COLLECTED IN 1994 AND 1995 [a]

Element	Old tea leaves	Fresh tea leaves	High level Cher. cont. soil	Low level Cher. cont. soil	Soil in pot	Soil in field of ÇNAEM
Na (%)	0.020 ± 0.08	0.017 ± 0.001	0.13 ± 0.01	0.29 ± 0.01	0.17 ± 0.01	0.64 ± 0.03
K (%)	1.1 ± 0.11	2.2 ± 0.22	0.75 ± 0.07	0.67 ± 0.06	0.47 ± 0.04	1.30 ± 0.12
Br	8.2 ± 2.9	3.6 ± 1.3	26 ± 23	20 ± 17	22 ± 18	20 ± 19
As	<3.0	<3.0	10 ± 1.2	9.9 ± 1.2	4.8 ± 0.09	17 ± 1.8
U	<2.9	<2.9	3.4 ± 2.5	4.2 ± 3.3	2.7 ± 2.2	4.3 ± 3.4
Se	<0.3	<0.3	4.4 ± 1.5	<1.1	2.0 ± 0.8	<1.1
Strontium	<140	<140	<81	<81	94 ± 80	<81
Sc	0.13 ± 0.012	0.32 ± 0.02	20 ± 0.87	20 ± 0.63	13 ± 0.41	17 ± 0.55
Zinc	13 ± 5.7	62 ± 5.6	120. ± 13	130. ± 12	80 ± 7.8	110. ± 9.0
Barium	140 ± 41	72 ± 40	220 ± 71	210 ± 61	140 ± 44	420 ± 100
Thorium	<0.10	0.22 ± 0.010	18 ± 1.2	15 ± 1.1	7.1 ± 0.50	12 ± 0.81
Cr	<1.0	4.2 ± 1.1	110. ± 13	83 ± 10	66 ± 7.9	140 ± 16
Caesium	<0.10	<0.10	5.6 ± 0.36	4.7 ± 0.33	2.6 ± 0.21	7.2 ± 0.38
Fe (%)	0.015 ± 0.037	0.11 ± 0.01	5.6 ± 0.17	5.8 ± 0.18	3.1 ± 0.10	4.2 ± 0.13
Cobalt	0.070 ± 0.040	0.36 ± 0.08	14 ± 0.55	16 ± 0.63	13 ± 0.49	25 ± 0.96
Sb	<0.03	<0.03	0.92 ± 0.18	0.79 ± 0.15	0.66 ± 0.13	1.1 ± 0.20
Nickel	<40	<40	<40	<40	<40	61 ± 40
Ca (%)	1.6 ± 0.57	0.68 ± 0.33	0.68 ± 0.50	0.80 ± 0.41	0.60 ± 0.36	5.4 ± 1.3

[a] Results presented µg/g dry mass (DM). Result values lower than the Limit of Detection are presented using '<'.

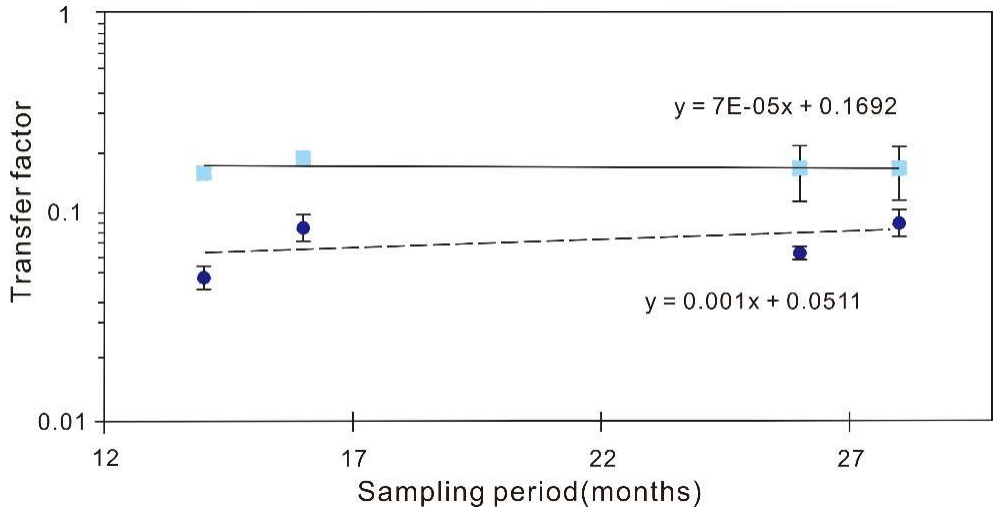

FIG. XIII-1. Transfer factors in leaves at several sampling dates (dotted line is for soil containing high activity concentrations of radionuclides of Chernobyl origin; solid line is for soil containing high activity concentrations of radionuclides of Chernobyl origin and additional artificial radionuclides).

XIII-4. DISCUSSION

In previous studies, concentrations of ^{137}Cs of Chernobyl origin in tea and thyme leaves were used to estimate the natural effective or biological half-lives [XIII-2, XIII-4. Moreover, the translocation and distribution of ^{137}Cs in different components of tea plant were investigated, both for caesium arising from foliar absorption and from root uptake from Chernobyl contaminated soil during 1987–1994 [XIII-5]. These studies showed that the transfer of radionuclide from soil to the plant occurred only in the roots during this period. Conversely, the data confirmed that the new leaves of the plant directly accumulated ^{137}Cs from the stem in the growing seasons following translocation of caesium from leaves to the stem, which occurred at the time of the accident.

Transfer factors of radiocaesium from soil to plants were variable and depended on many parameters [XIII-6–XIII-9]. In the present study, the mean TF of ^{137}Cs of tea leaves were 0.069 and 0.146 for soils of type a_1 and a_2, respectively. The TF of caesium in tea leaves from Chernobyl contaminated soil in the same region and on the same date was 0.055 ± 0.11 [XIII-10] which is in good agreement with the estimated value of 0.069, only for Chernobyl contaminated soil. Conversely, TF for soil type a_1 differ considerably from those for soil of type a_2. After the Chernobyl accident, caesium was strongly bound to soil constituents, especially to mineral and organic materials, of which less than 10% was considered mobile [XIII-11]. For this reason, sequential extraction techniques should be used to investigate the degree of binding of deposited ^{137}Cs to soil components.

Radiocaesium has similar chemical and metabolic behavior to potassium which is an essential element for plant nutrition [XIII-12]. In the literature, exchange, fixation and uptake processes of caesium are similar to those of potassium [XIII-13]. The mobility of radiocaesium in soil depends on the concentration of stable caesium and potassium, which compete for adsorption sites [XIII-14]. In the present study, no correlations of TF were found between potassium and radiocaesium activity concentrations of crops and soils shown in Tables XIII-1, XIII-3 and XIII-5. In previous studies, no correlation was observed between absorbed radiocaesium and available amounts of potassium in soil [XIII-15], or between potassium contents of plant parts

and TF of ^{137}Cs [XIII-16, XIII-17]. However, the TF of radiocaesium in thyme leaves from field experiments were lower than for thyme leaves collected from the pot experiment (see Tables XIII-3 and XIII-4).

The TF of ^{134}Cs for thyme plants in the field were lower in winter than in summer. This result shows a good agreement with the results obtained for spinach and wheat crops [XIII-17]. In another previous study, it was indicated that clay minerals have a strong binding capacity [XIII-18]. In the present work, the clay concentration in the field soil was higher than in the pot soil (see Table XIII-4), which may explain the higher TF of ^{134}Cs for thyme determined in the pot experiment.

A previous study indicated that there was no correlation between the concentration of ^{137}Cs in plant and stable element in soil [XIII-19]. Conversely, it was also indicated that the distribution coefficient, K_d, was highly reduced after small additions of stable caesium [XIII-7]. In our study, the concentration of stable caesium was higher in the soil used for field experiment than for the pot experiment (Table XIII-5). The TF of ^{134}Cs in thyme leaves ranged from 0.15 to 0.61, which is in fairly good agreement with TF determined previously for grass, which ranged from 0.02 to 0.2 [XIII-20].

XIII-5. ACKNOWLEDGMENTS

We wish to thank the Tea Research Institute (Rize, Turkey) for its cooperation in the collection of the tea samples and The Soil Laboratory of Village Employment of 18th Region Directory in Istanbul for soil analyses at the time of the CRP.

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ANNEX XIV.

DETERMINATION OF TRANSFER FACTORS FOR RADIONUCLIDES, INCLUDING ^{137}CS AND ^{85}SR, IN FRESHWATER FISH AND PLANT CROPS FROM TROPICAL AND SUB-TROPICAL AUSTRALIA

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XIV-1. OBJECTIVES

The specific activities in Australia for the CRP were threefold. They comprised:

(1) A review of existing radionuclide TF data for tropical and sub-tropical areas of Australia, Papua and New Guinea and the south-western Pacific region;
(2) Field sampling of freshwater fish and a variety of crops, together with associated water and soil, for analysis of activity concentrations of ^{137}Cs derived from previous deposition of atmospheric contamination due to nuclear weapons testing or accidental release; and
(3) Experimental assessment of the TF for ^{137}Cs and ^{85}Sr between freshwater and the teleost fish, *Bidyanus bidyanus*, which is native to sub-tropical inland rivers of Australia.

The overriding aim for each of these activities was to complement contributions from other participants and existing data so as to identify or to fill gaps in the IAEA database for tropical and sub-tropical TF.

Quality assurance mechanisms were put in place to determine and improve the accuracy of analyses carried out within the laboratories involved. Details of these aspects of the study and of the Australian contribution to them are detailed in Annex I of this Supplementary File.

Each of the activities outlined above were carried out separately. Hence this report will address each section independently.

XIV-2. REVIEW OF EXISTING DATA

XIV-2.1. Procedure

A comprehensive literature search was undertaken using the following on-line databases: INIS, Streamline, Georef, and BIOSIS. The search was done for any data on the use or measurement of radionuclides in experimental trials or field surveys within the region comprising tropical and sub-tropical Australia, Papua and New Guinea and the South-western Pacific. The search was restricted to freshwater and terrestrial ecosystems. Reference lists in manuscripts, as well as bodies of known data, were used to identify additional information.

In some cases, TF were given with no reasonable validation by way of sampling protocol or other relevant details. These data were considered as generic and hence they were excluded. Similarly, values in which the radionuclide concentration in either the supporting medium or the organism were beyond the limit of detection for analysis, resulting in less than or greater than numbers, were also excluded. The validity of the values themselves in relation to sampling and analytical procedures and errors was more difficult to assess. In some cases the procedures used were mentioned without elaboration, although there was sufficient detail to suggest that correct procedures were followed. Where errors were reported, their magnitude was often as great as the values themselves, as is often the case for environmental sampling. For the purposes of this report the TF were collated “as is” or derived from reported source and sample activities

without reference to their errors, reported or otherwise. This action was based on the observation that the spread of data within any set usually greatly exceeded the error estimates for individual values.

XIV-2.2. Results

For areas of the region encompassed by the survey, excluding Australia, no data were identified that was appropriate to the requirements of the CRP. Some radiometric data were available, but they did not relate the radioactivity in biota to supporting media. In relation to artificial radionuclides, the Australian data were mainly limited to nutrient and metabolic studies with radionuclides such as ^{32}P, ^{14}C, and various nitrogen isotopes, which were carried out in temperate regions of the continent. There was some information on iodine in milk for tropical regions of Australia, collated in the '60s following atmospheric nuclear testing in the South Pacific, but the results were reported as dose estimates with no numbers to determine accumulation and TF.

For the purposes of this study, useful information was restricted to radionuclides in the uranium- and thorium-series in relation to proposed, existing and past mining operations in the Northern Territory and Western Australia. Table XIV-1 gives a summary of the findings for FM data. For each isotope, the values were separated into classes according to the general type of organism and the source of the isotope to the organism. For all general classes an arithmetic mean was initially derived. In almost every case, this value was in excess of the median value(s) for the data subset. This indicates non-normal distributions with positive skew. To provide a better estimate of central tendency the geometric means were determined using log transformations.

Several references dealt with the relationships between organisms and the environment with regard to bioaccumulation of radionuclides. Some of these did not provide TF values, but investigated the mechanisms behind accumulation. A few species, particularly the freshwater mussel *Velesunio angasi* and the water lily *Nymphaea violacea*, have been studied in some detail in regard to ^{226}Ra accumulation. This was principally because these organisms are significant dietary components of a critical group exposure pathway: Aboriginals living downstream of a uranium mine.

XIV-2.3. Discussion and conclusions

When interpreting the information in Table XIV-1 it is important to recognize the generalizations used in formulating it. The biota categories, animals and plants, both comprise all terrestrial and aquatic species across all trophic levels. Nonetheless, the data in Table XIV-1 confirm that TF relating to water samples are generally higher than those for corresponding sediment or for uptake from soils. This reflects the fact that sediments act as a sink for radionuclides in aquatic systems and that the radiocaesium is much less available for uptake once it is bound in sediments and soils. The TF also reinforce the finding that radiological dose from natural radionuclides can be significant and may be of a higher order than that due to contamination by artificial radionuclides (e.g. see below).

TABLE XIV-1. TRANSFER FACTORS FOR URANIUM AND THORIUM SERIES RADIONUCLIDES IN TROPICAL AND SUB-TROPICAL AUSTRALIA [a]

Element	Isotope	Biota	Medium	Geometric mean (kg/kg)	Range		No. of observations
					- GSD [c]	+ GSD	
Uranium	U-238	Plant	Water	280	110	720	14
		Plant	Soil/sediments	0.35	0.067	1.9	40
		Animal	Water	38	5.0	280	38
		Animal	Soil/sediments	0.005 2	0.002 1	0.013	22
	U-234	Plant	Soil/sediments	0.009 0	n.a. [b]	n.a.	1
Radium	Ra-226	Plant	Water	38	n.a.	n.a.	1
		Animal	Water	130	17	940	78
		Plant	Soil/sediments	0.027	0.009 6	0.078	2
Polonium	Po-210	Animal	Water	490	66	3600	52
		Animal	Soil/sediments	0.022	0.004 3	0.11	6
Lead	Pb-210	Animal	Water	53	6.1	460	24
		Plant	Soil/sediments	0.027	0.011	0.066	2
		Animal	Soil/sediments	0.001 8	0.000 69	0.004 6	4
Thorium	Th-228/230	Animal	Plant	1.3	0.77	2.1	8
	Th-230	Animal	Water	50	n.a.	n.a.	1
	Th-228/230/232	Plant	Soil/sediments	0.0082	0.0051	0.013	4

[a] TF for crops were converted to fresh mass (FM) for consistency on an assumed ratio of 10:1 (see text).
[b] n.a. Not applicable.
[c] GSD: Geometric Standard Deviation.

In comparison with recommended values from marine data [XIV-1], the mean TF in freshwater systems appear to be of the same order for uranium. For all other radionuclides the mean tropical freshwater concentration factors are 1 to 2 orders of magnitude lower than the recommended marine values. Temperate plant-to-soil TF listed by the IAEA [XIV-2], most of which are determined on a dry mass (DM) basis, are slightly lower for all radionuclides when compared with values given in Table XIV-1 and assuming a FM (fresh mass) to DM ratio of 10. Concentration factors of radionuclides in the uranium- and thorium-series for freshwater fish are approximately equivalent between temperate and tropical systems. The statistical significance of any of these differences cannot be assessed without access to the complete data sets.

In relation to the studies concentrating on radium accumulation in foods stuffs of the Aboriginal diet, two different modes of accumulation were noted, both of which imply that models based on linear TF may be inappropriate. In mussels, most of the radium was accumulated in insoluble phosphate granules within the soft edible tissues of the organism [XIV-3]. The accumulation kinetics were linear over the range of concentrations and time spans studied and there was no significant loss. Hence, there was no equilibrium concentration, or concentration factor, for radium in these animals. The biological half-life of accumulated radionuclides was inversely correlated with the solubility of the element as a phosphate [XIV-4].

In contrast, radium achieved equilibrium between water or sediment and the tissues of the waterlily [XIV-5]. However, the data indicated that the TF between water and foliage was non-linear with respect to radium concentration in the water. A better fit is provided by a log-log regression of the data providing a Freundlich adsorption isotherm. Davy and Conway [XIV-6] found a similar, non-linear pattern of accumulation for both radium and uranium in mussels.

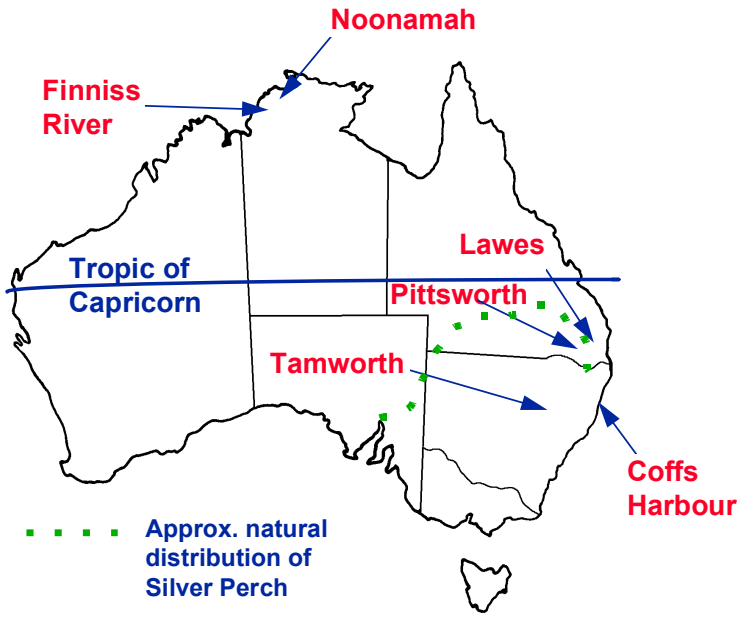

FIG. XIV-1. Map of part of Australia showing the sampling sites for freshwater fish and crops. The natural distribution of silver perch is also shown.

Additionally, the accumulation of radium from water by both mussels and water lilies was reduced with increased calcium and magnesium concentrations. These findings support the general hypothesis that radium is accumulated as an analogue for these divalent nutrient cations. Other parameters known to be significantly related to uptake are age in mussels [XIV-7] and tissue condition in water lilies [XIV-8].

XIV-3. FIELD SAMPLING AND ANALYSES

The aim of the field survey was to determine the present day of ^{137}Cs concentration in the edible parts of freshwater fish and crops as well as that in the supporting water or soil.

XIV-3.1. Materials and methods

Samples of crops and fish were collected from a number of locations in tropical and sub-tropical Australia (Fig. XIV-1). In general, crops were harvested in season. For fruit, 1 kg soil samples were taken at the same time as the crop and comprised composites, to a depth of 20 cm, taken at cardinal points 1 m from the base of the tree or below the perimeter of the foliage. For broadacre crops, triplicate 1 kg soil samples were taken from the field after cropping was completed. Plant samples were kept separate from soils after harvest.

Fish were collected by netting or angling at two sites (A and B), on the Finniss River, N.T., within a few days of each other. Edible portions of fish were taken for analysis. Filtered water samples (0.45 µm; 220 L, 354 L) were collected on the same day as the fish were taken. Stable caesium was added to the water as a carrier and yield tracer. The caesium was then extracted from solution using a slurry of ammonium molybdophosphate (AMP) [XIV-9].

All samples were dried. Stable element analyses were performed on all samples after gamma spectrometry.

XIV-3.2. Results

The results of the radiometric analysis of fish and water are given in Table XIV-2. The results for crops and soils are given in Table XIV-3. 'Less than' values were included as they provide upper limits of the TF in biota for which little or no other information is available.

As expected for a sampling programme for the Southern Hemisphere, all caesium values are very low. This was exacerbated by the elapsed time since the cessation of atmospheric testing and the lower deposition rate in tropical compared with temperate areas. For all fish samples, values were not significantly different from background.

XIV-3.3. Discussion and conclusions

The high concentration factors reported for fish, given as less than values, are an artefact of the low ^{137}Cs concentration in the large volume water samples together with the relatively small masses used for the tissue sample analyses. In addition, they were determined on a DM basis, which can inflate ratios in comparison to fresh weight data. The expected TF of caesium for temperate freshwater fish flesh is 2000 [XIV-2]. It is unclear if this value was based on FM or DM.

Similarly, most of the plant data are at or near the detection limits and hence should be treated cautiously. Sorghum was identified as an important crop in tropical regions for which no TF information was available. The results indicate that this crop has a low TF for caesium.

Comparative data for temperate crops are given in [XIV-2]. In that document, the caesium TF range from 0.005 (irrigated rice) and 0.01 (cereal), to 0.46 (mixed green vegetables) and 0.53 (grass). The tropical data in Table XIV-3 are of the same order as the temperate data given the uncertainties in their calculation.

Any caesium present in the tropical soil samples has been there for some considerable time, and hence is likely to be tightly bound to exchange sites. As such, it is reasonable to expect that any freshly deposited caesium, e.g. in the case of any future nuclear accident, is more likely to be available for bioaccumulation. From this, it is recommended that the non-citrus fruits such as banana, avocado, rambutan and paw paw, that had generally higher TF than the grains and seeds, be studied in more detail to investigate their accumulation of freshly deposited ^{137}Cs.

XIV-4. EXPERIMENTAL STUDY

XIV-4.1. Aim

One of the initial aims of the CRP was to identify areas where little or no data were presently available on TF in tropical and sub-tropical environments for critical radionuclides. From that initial survey, freshwater fish were identified as being one area critically requiring additional experimental and field survey data. Hence, experimental studies were initiated to determine radionuclide TF to be used in dose assessment model databases for tropical and sub-tropical ecosystems.

In specifically addressing the aims of the CRP, the species chosen for the Australian study was Silver Perch (*Bidyanus bidyanus*). This fish is a common, edible, sub-tropical species native to inland rivers. As a Teraponid, it is closely related to many other edible species across south-east Asia.

TABLE XIV-2. RESULTS OF ANALYSIS OF CS-137 ON SAMPLES FROM THE FINNISS RIVER, NORTHERN TERRITORY, AUSTRALIA

Site	Sample		Activity concentration		Transfer factor (L/kg DM)
	Common name	Scientific Name	Biota (Bq/kg DM)	Water (Bq/L)	
A	Sleepy cod	*Oxyleotris lineolatus*	<0.3 [a]	0.0001 4	<2 100
	Barramundi	*Lates calcarifer*	<0.3	0.0001 4	<2 400
	Banded grunter	*Amniataba percoides*	<1.9	0.0001 4	<1 4000
	Tarpon	*Megalops cyprinoides*	<0.6	0.0001 4	<4 200
	Black bream	*Hephaestus fuliginosus*	<0.5	0.0001 4	<3 600
B	Tarpon	*Megalops cyprinoides*	<0.6	0.0001 1	<5 300

[a] The value of the measurement result is less than the Limit of Detection.

TABLE XIV-3. RESULTS OF ANALYSIS OF CS-137 IN DRY CROPS AND ASSOCIATED SOILS FROM TROPICAL AND SUB-TROPICAL AREAS OF AUSTRALIA

Location	Crop	Variety	Activity concentration (Bq/kg)		Transfer factor (kg/kg DM)
			Crop	Soil	
Pittsworth, Queensland	Sesame seed	Aussie gold	0.09	1.2	0.06
	Mung beans	Berken	<0.06 [a]	1.2	<0.05
Lawes, Queensland	Sorghum	Satin	<0.05	1.8	<0.03
	Mung beans		0.12	1.5	0.08
	Soy beans		0.08	1.2	0.06
Coffs Harbour, New South Wales	Banana		<0.27	5.4	<0.05
			0.28	5.4	0.05
	Avocado		0.57	4.1	0.14
			0.17	4.1	0.04
Tamworth, New South Wales	Sorghum	Buster 1	<0.03	3.4	<0.01
		Buster 2	0.07	3.4	0.02
		Buster 3	<0.04	3.4	<0.01
		DeCalb 3GY/DK35	<0.02	3.0	<0.01
		DeCalb 3GY/DK35 2	<0.05	3.0	<0.02
		DeCalb 3GY/DK35 3	0.06	3.0	0.02
Noonamah, Northern Territories	Banana	Ruby	0.55	0.8	0.67
	Grapefruit		<0.14	2.1	<0.07
	Lime	Meyer	<0.27	1.5	<0.19
	Lemon		<0.50	1.5	<0.33
	Paw paw		1.25	1.1	1.15
	Rambutan		0.70	1.0	0.70
	Mango		<0.44	1.8	<0.24

[a] The value of the measurement result is less than the Limit of Detection.

The work carried out in this section of the project has been published in some detail elsewhere [XIV-10]. Hence, this section will only briefly describe the experimental details and provide a summary of the pertinent findings. The implications of these results, in terms of dose assessment, will also be addressed.

XIV-4.2. Materials and methods

In duplicate tanks, adult *B. bidyanus* were exposed in the laboratory to ^{137}Cs and ^{85}Sr in freshwater at average activities of 850 ± 20 Bq/L and 1050 ± 20 Bq/L, respectively. Flow-through experimental conditions were applied and natural sub-tropical conditions were simulated as far as practicable including the use of sediment. The basic experimental protocol is described in Annex II of this Supplementary File. There were no significant differences between the duplicate exposure tanks for any water quality parameters.

Prior to the exposure of fish, K_d values between the sediment and water were determined. These were found to be 0.2 ± 0.4 L/g and 7.5 ± 0.3 L/g for ^{85}Sr and ^{137}Cs, respectively. These values were used to label the sediments prior to the introduction of fish.

XIV-4.3. Results

The accumulation of radioactivity by the flesh of the fish during the experiment is shown in Fig. XIV-2. Overall concentration factors for the edible flesh of 13 ± 5 kg/L for ^{137}Cs and 0.7 ± 0.2 kg/L for ^{85}Sr were determined (FM basis). Non-linear regression fitting of a 1-compartment exponential uptake and loss model, constrained using the derived equilibrium concentration, derived half-times of 19 ± 2 days for ^{137}Cs and 5 ± 1 days in the case of ^{85}Sr. Assuming the model to be appropriate, these values controlled the overall rate at which equilibrium was achieved. Larger fish accumulated slightly, but significantly less than smaller animals.

The distribution of radionuclides between tissues of the fish, shown in Fig. XIV-3, confirmed that ^{137}Cs was more concentrated in the flesh than in the bone or skin on a fresh weight basis and that all 3 tissues were either at or approaching equilibrium after 8 weeks. However, ^{85}Sr was much more concentrated in the bone than in the flesh. The concentration in bone was still increasing rapidly at the end of the exposure. Due to uptake into the scales, skin samples were similar in ^{85}Sr concentration to the bone samples.

XIV-4.4. Discussion and conclusions

Concentration factors were lower than the expected values given in the literature for temperate freshwater ecosystems but support recently reported values from other tropical studies within, and external to the CRP [XIV-10]. As such, the results imply that the use of generic dose assessment models for caesium and strontium uptake by fish in tropical freshwater environments, which assume that only flesh is consumed, may be overly conservative.

The half-times measured indicate that approximate equilibrium, between the activities in fish flesh and water, would be achieved within 100 days in the case of ^{137}Cs, or 25 days in the case of ^{85}Sr. These low values were generated using the generic one-compartment model used in the experimental protocol. It is probable that a multi-compartment model may be more appropriate and that real half-lives would be somewhat different from those generated by the generic model.

The biodistribution analysis implied that concentration in scales may contribute significantly to dose assessment from strontium in diets where scales may be included in the preparation of meals for human consumption.

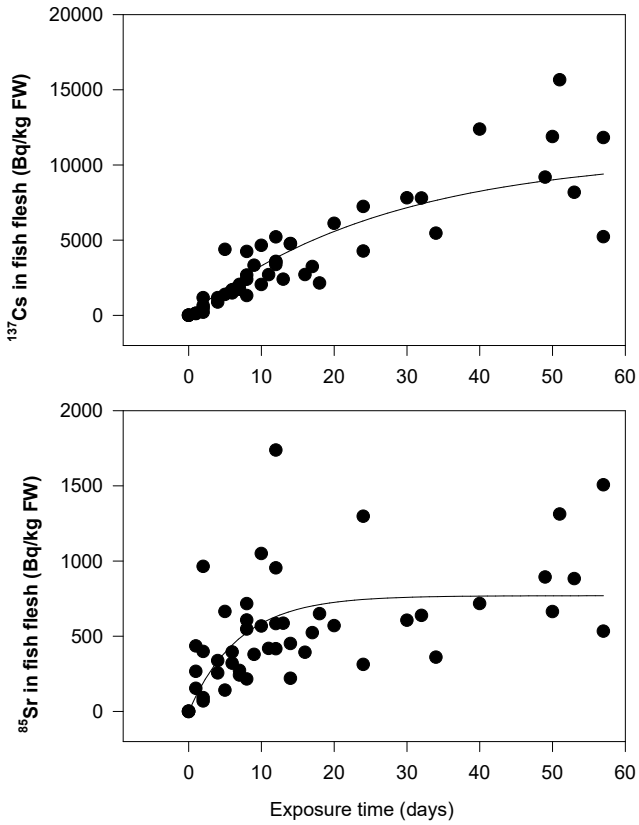

FIG XIV-2. Uptake of radionuclides by flesh of B. bidyanus (FM basis) with one-compartment exponential uptake models fitted.

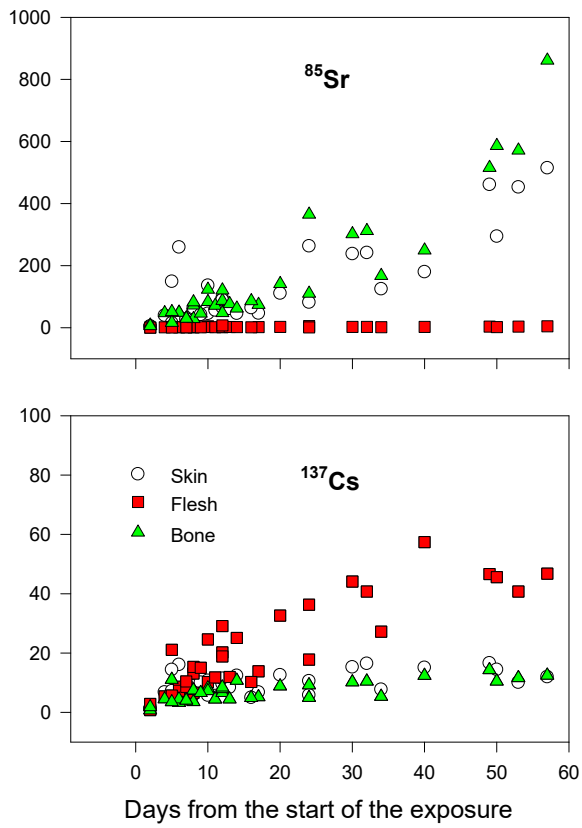

FIG XIV-3. Biodistribution of ^{137}Cs and ^{85}Sr between flesh, skin/scales and bone of B. bidyanus.

XIV-5. SUMMARY

The TF determined in this study as part of the CRP were generally consistent with, or lower than previous data acquired for temperate zones. Some caution is needed in interpreting these results because of the low environmental concentrations in the region, due to low fallout radiocaesium deposition. In particular, this has given rise to high error terms in the field sampling data. Nonetheless, low concentration factor values for radiocaesium and radiostrontium were also recorded in the laboratory experiments using tropical freshwater fish.

The authors identified through literature search literature search that it might be the case that the prospect that TF models which assume linearity may be over- or under-estimating dose. For example, there was evidence, from studies on radium in waterlilies, that TF were reduced at higher environmental activity concentrations. Alternatively, radium in mussels was shown experimentally to be continually accumulated over the lifetime of the organism, never achieving a stable activity concentration irrespective of water activity concentrations.

Due to the likelihood that present day caesium is strongly absorbed to sediments and soils, it is recommended that additional studies of bioaccumulation by tropical fruit such as bananas, avocado and paw paw be undertaken. These non-citrus foods had higher TF than other crops and it is possible that their TF values may increase when caesium is freshly deposited and hence more available for uptake.

The fish experiment confirmed findings of other participants in the CRP that TF for caesium and strontium were lower in tropical fish than in temperate species. The biological half-lives of these radionuclides were also shorter in warmer climates, implying more rapid achievement of equilibrium in contaminated systems. The heavy contamination of skin and scales with strontium was also identified as a possible concern for some critical group dose estimation models where whole fish, rather than fillets, were consumed.

XIV-6. ACKNOWLEDGMENTS

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ANNEX XV.

RADIONUCLIDE TRANSFER FACTORS AND THEIR PARAMETERS OBTAINED IN JAPAN'S TERRESTRIAL ENVIRONMENT

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XV-1. INTRODUCTION

Ingestion is one of the important pathways by which radionuclides enter the human body, after routine and/or accidental release of radionuclides from nuclear facilities to the environment. Eating habits, however, differ from country to country. In European and North American countries, the contribution from livestock products including meat, eggs and milk is large, whereas in Asian and South American countries agricultural products, including cereals and vegetables, are the main contributors [XV-1]. In Japan, for example, the staple food is rice.

Regional characteristics such as soil and plant types affect significantly the behaviour of radionuclides in the soil-crops system. Technical Report Series No. 364 [XV-2] provided environmental transfer data but was primarily related to temperate environments. A revision was made to update and provide more data from other climate environments [XV-3]; however, numbers of transfer parameter data are still limited in non-temperate environments. Although Japan is in a temperate climate, because soil-crop systems are different from European and North American countries, providing data are of help to understand the effect of the regional characteristics to the environmental transfer parameters. The purpose of this study was to provide relevant transfer parameters such as soil-to-crop TFs and soil-soil solution distribution coefficients (K_ds) in Japan. Previous experimental results obtained within the CRP "Transfer of Radionuclides from Air, Soil, and Freshwater to the Food Chain of Man in Tropical and Sub-tropical Environments" (1993–1997) were summarized together with new experimental data and data from relevant studies carried out in Japan.

XV-2. SOIL TO CROP TRANSFER FACTORS

The TF, or F_v in IAEA TRS 472 [XV-3], is calculated from the activity concentrations of radionuclide in both crop and soil samples. The TF is defined as follows:

$$TF = \frac{C_{crop}}{C_{soil}} \quad \text{(XV-1)}$$

where C_{crop} is the activity concentration of radionuclide in the crop (Bq/kg dry weight (DM)) and C_{soil} is that in the soil (Bq/kg DM). The equation is also used to obtain TF of stable element using the mass concentration of stable element in the crop (mg/kg DM) and that in the soil (mg/kg DM).

XV-2.1. Uptake experiments of radionuclides by crops

XV-2.1.1. Materials and Methods

Andosol (a major soil type in Japan, derived from volcanic origin material) was collected in Ibaraki, Japan. Soil samples were air-dried and passed through a 2-mm mesh sieve. The pre-treated soil sample of about 3 kg in weight was weighed and mixed thoroughly in a 10 L plastic container with 5 g of chemical fertilizer (N: P: K=12:16:14) and five radiotracers, i.e. $^{137}CsCl$, $^{85}SrCl_2$, $^{54}MnCl_2$, $^{60}CoCl_2$ and $^{65}ZnCl_2$ (carrier free). Then the soil sample was

transferred to a Wagner pot of about 3000 cm^3 in volume (diameter: 16 cm, height: 15 cm). Two to three pots were prepared for each crop species.

The vegetables were selected amongst common vegetables consumed in Japan, such as cabbage (*Brassica oleracea* L. *var. capitate* L.), Chinese cabbage (*Brassica campestris* L. var. *pekinensis* RUPER.), komatsuna (*Brassica rapa* L. *var. perviridis* BAIL.), lettuce (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L.), carrot (*Daucus carota* L.) and soybean (*Glycine max* L. MERR.). Young seedlings (or seeds) were planted in the pots with spiked soil. For rice plants, the pots were soaked with water in advance and then two rice plant seedlings (*Oryza sativa* cv. Nihonbare), about 3 weeks from germination, were planted in each pot. These pots were placed in a plant growth chamber (Puffer-Hubbard 38-15 HLE, Puffer-Hubbard CEC38-15HLE or Koito Koitotoron) with a light intensity of about 50 000–70 000 lux at the top of the plants. Temperature, moisture and the day-night cycle were controlled to simulate the outdoor conditions in Ibaraki, Japan. In addition, we have carried out uptake experiments with the same crops using ^{125}I and ^{95m}Tc tracers as I^- and TcO_4^-, respectively. These experiments were carried out separately.

At harvest, three samples of the edible part of each plant were taken from each pot. Soil samples from different depths also were collected. Thereafter the plant samples were freeze-fried, and the soil samples were dried in an oven at 110°C. Activity concentrations of radionuclides in each sample were measured with a Ge detector system (Seiko EG&G) for the mixture of radioactive ^{137}Cs, ^{85}Sr, ^{54}Mn, ^{60}Co and ^{65}Zn. A well-type NaI(Tl) scintillation counter (Aloka ARC-300) was used for ^{125}I or ^{95m}Tc measurement. Decay corrections were made to the beginning of the experiments.

XV-2.1.2. Transfer factors of radionuclides for rice

The TF values obtained by the radiotracer studies [XV-4–XV-7] are shown in Table XV-1. The TF values of ^{137}Cs and ^{85}Sr for brown rice (hulled rice) are 1.7×10^{-2} and 6.0×10^{-2} (all on a DM basis). For ^{60}Co and ^{125}I, their TF showed the same value of 6.0×10^{-3}. The TF values of ^{54}Mn and ^{65}Zn were usually higher than those of Cs, Sr, Co and I, because Mn and Zn are essential elements for plant nutrition. Compared to the reported TF value for Tc in grains of upland field cereals (arithmetic mean value: 1.3×10^0 [XV-3]), an extremely small value was found for hulled paddy rice (5.0×10^{-5}). Yanagisawa et al. [XV-8] reported that the activity concentration of Tc in the soil solution collected from the flooded soil decreased rapidly with time. In the case of wheat plants grown in a non-flooded soil, the decrease in technetium activity concentration in the soil solution was rather slow. It has been suggested that the technetium tracer, added as TcO_4^- to the paddy soil, was readily transformed to insoluble forms under the reducing conditions in the flooded soil [XV-9].

Our data show that the TF of radionuclides for rice are much smaller than those of other vegetables described in the next section. This might be due to the lower accumulation of these elements in grains in comparison to leaves.

TABLE XV-1. TRANSFER FACTORS OF RADIONUCLIDES FROM SOIL TO BROWN RICE (HULLED RICE)

Soil type	Transfer factor (on a DM basis)						
	Cs	Sr	Mn	Co	Zn	I	Tc
Andosol	1.7×10^{-2}	6.0×10^{-2}	2.1×10^{-1}	6.0×10^{-3}	3.0×10^{0}	6.0×10^{-3}–7.0×10^{-3}	5.0×10^{-5}
Gray lowland soil	— [a]	—	—	—	—	1.1×10^{-3}–2.7×10^{-3}	6.0×10^{-4}
References	[XV-4]	[XV-4]	[XV-4]	[XV-4]	[XV-4]	[XV-5 – XV-6]	[XV-7]

[a] —: Data not available.

TABLE XV-2. TRANSFER FACTORS OF RADIONUCLIDES FROM SOIL TO CROPS CONSUMED IN JAPAN

Vegetables	Transfer factor (on a DM basis)							Reference
	Cs	Sr	Mn	Co	Zn	I	Tc	
Cabbage	8.1×10^{-1}	8.1×10^{-1}	1.4×10^{0}	8.1×10^{-2}	6.9×10^{-1}	1.6×10^{-3}	1.3×10^{0}	XV-11–XV-13
Chinese cabbage	9.4×10^{-1}	9.4×10^{-1}	1.7×10^{0}	1.1×10^{-1}	2.1×10^{0}	—	8.0×10^{-1}	XV-11–XV-12
Komatsuna	4.8×10^{-1}	$3.7\ \mathrm{x}10^{0}$	2.5×10^{0}	1.3×10^{-1}	1.4×10^{0}	1.6×10^{-2}	1.1×10^{1}	XV-11–XV-13
Lettuce	7.9×10^{-1}	2.6×10^{0}	1.0×10^{1}	6.9×10^{-2}	3.4×10^{0}	6.7×10^{-3}	—	XV-12, XV-14
Spinach	1.4×10^{0}	2.5×10^{0}	1.2×10^{1}	1.5×10^{0}	1.4×10^{1}	3.1×10^{-3}	1.7×10^{1}	XV-11–XV-13
Carrot	— [a]	—	—	—	—	9.0×10^{-4}	1.9×10^{0}	XV-11, XV-13
Yam	—	—	—	—	—	3.0×10^{-4}	—	XV-13
Sweet potato	—	—	—	—	—	2.0×10^{-4}	8.0×10^{-2}	XV-11, XV-13
Onion	—	—	—	—	—	1.1×10^{-2}	5.0×10^{-1}	XV-11, XV-14
Tomato	—	—	—	—	—	3.0×10^{-4}	3.0×10^{-1}	XV-11, XV-13
Radish	—	—	—	—	—	1.5×10^{-3}	—	XV-13
Soybean	—	—	—	—	—	3.0×10^{-3}	—	XV-13
Burdock	—	—	—	—	—	5.0×10^{-4}	—	XV-13
Wheat	—	—	—	—	—	5.0×10^{-4}	3.0×10^{-2}	XV-10, XV-14

[a] —: Data not available.

XV-2.1.3. Transfer factors of radionuclides for vegetables

The radionuclides TF values for vegetables are given in Table XV-2 [XV-10–XV-14]. Significant differences in the TF values of ^{137}Cs were observed among the vegetable species, and the range were from 9.0×10^{-3} to 1.4×10^{0}. The TF values of ^{85}Sr showed a narrower range (8.1×10^{-1}–3.7×10^{0}) than those for Cs.

Although cabbage, Chinese cabbage and komatsuna are from the same Brassica family, the TF of Sr for komatsuna was about four times higher than those for the other two crops. To explain this tendency, concentration ratios of ^{85}Sr were calculated for leaves of cabbage and radish (a non-headed leaf vegetable similar to komatsuna) and compared to the leaf at first position from outside using ^{85}Sr data by Ban-nai et al. [XV-12, XV-14] (the results are shown in Fig. XV-1A). For cabbage, the ^{85}Sr concentrations in younger leaves (inner position) are considerably lower than those in the old leaves (outer position), while the concentration in younger leaves of radish were low but not as low compared to cabbage. Although plant families were different, leaves of lettuce showed a similar Sr distribution to those of cabbage, and leaves of spinach showed a similar Sr distribution to those of radish (Fig. XV-1B). These trends suggest that Sr which has been absorbed through the roots is transported to the leaves and accumulates there, while water transpires from the leaves. The lower TF values obtained for the inner parts of cabbage and Chinese cabbage can then be attributed to the small amount of transpiration from the inner part of these plants which are tightly packed. Our findings agreed with those of Nisbet and Shaw [XV-15]. They also reported that the strontium distribution for the outer leaves was higher than those for the inner part of cabbage. Furthermore, they mentioned that the outer leaves are highly transpiring tissues and responsible for most of the xylem transport of calcium ions and analogues such as strontium. Therefore, accumulation of strontium in the outer leaves was higher than in the inner ones.

Usually caesium is strongly sorbed on soil. However, it is well known that Andosol contains organic matter and alophen in high concentrations [XV-16]. Since the sorption of caesium by soil organic matter and alophen is not strong, it is expected that plants take up the nuclide relatively easily from Andosol.

The TF values of ^{54}Mn and ^{65}Zn were higher than those of other radionuclides. This tendency was also observed in rice. Table XV-2 shows that the TF of iodine are very small, but those of technetium are high, particularly for leafy vegetables.

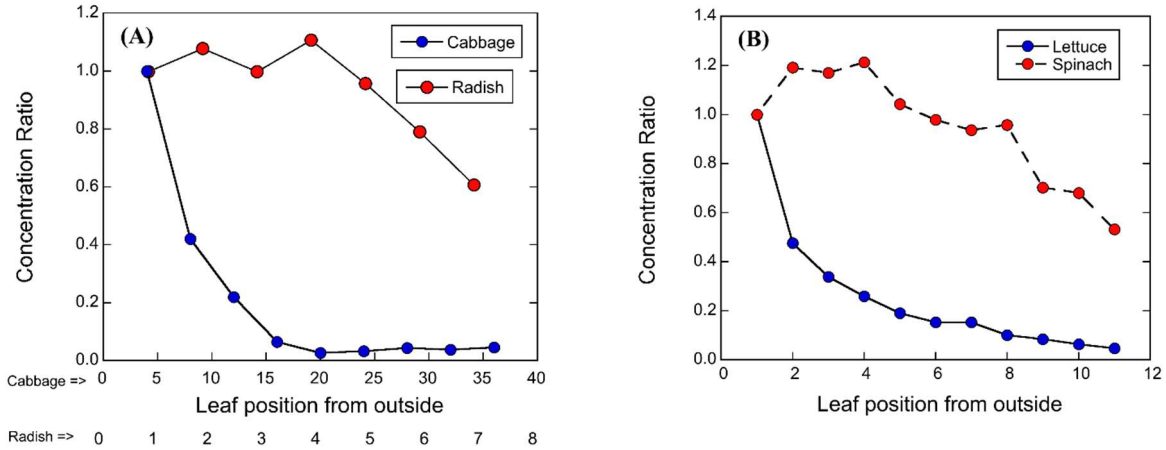

FIG. XV-1. Concentration ratio of ^{85}Sr between leaves positioned from outside and the first position from outside for cabbage and radish (A) and for lettuce and spinach (B).

XV-2.2. Transfer factors of indigenous elements from soil to rice and wheat

XV-2.2.1. Materials and methods

Paddy soils (ploughed soil layer: 0–ca. 15 cm) have been collected nationwide from 11 sampling sites and rice plants grown on these soils have also been collected in the harvesting season. Rice varieties grown traditionally in Japan are classified as short-grain types. Wheat grains and the associated soils were collected at 7 sampling sites by the National Institute of Agro-Environmental Sciences. Each rice sample was processed into brown rice (with bran) and polished rice (without bran). The average weight ratio of the polished rice to the brown rice was 0.9 (90% yield). The wheat grains were husked. The soil samples were air-dried and passed through a 2 mm mesh sieve. The soil and crop samples were ground into fine powder, separately.

To measure element concentrations, inductively coupled plasma mass spectrometry (ICP-MS) or inductively coupled plasma optical emission spectrometry (ICP-OES) were used. Solution samples are usually used for ICP-MS and ICP-OES; thus, solid samples have to be dissolved with mineral acids (a mixture of HNO_3, HF and $HClO_4$) using a microwave digester (CEM, MARS 5). Sample amounts used were 100 mg for soils and 500 mg for crops, and the samples were made in duplicate. After microwave digestion, each sample was evaporated to near dryness and the residue was dissolved in 20 mL of 2% HNO_3. All the acids used were ultra-pure analytical grade (Tama Chemicals, AA-100). About 40-50 elements, including Cs, Sr, Th and U, in both crop and soil samples were measured using ICP-MS (Agilent 7500, Yokogawa) and ICP-OES (VISTA Pro, Seiko) after diluting the acid solutions to a suitable concentration. Details were reported by Uchida et al. [XV-17].

To obtain TFs of stable iodine from agricultural soils to edible part of crops in Japan, soil samples from 79 upland fields and 63 paddy fields were collected nationwide in Japan from 2002 to 2006 during the harvesting season. Numbers of samples were: leafy vegetables, 22 (7 cabbage, 4 Chinese cabbage, 4 leek (green part), 2 lettuce, 2 spinach, 1 Nozawana, 1 Japanese radish, and 1 carrot); root crops, 14 (7 Japanese radish, 4 onion, and 3 carrot); tubers, 11 (6 potato, 3 sweet potato, and 2 taro); fruit vegetables, 18 (6 tomato, 5 eggplant, 4 cucumber, 2 green pepper, and 1 bitter cucumber); legumes, 7 (6 soybean and 1 peanut); cereals except rice, 9 (7 wheat and 2 barley); and rice, 63 (brown rice, polished rice, and bran).

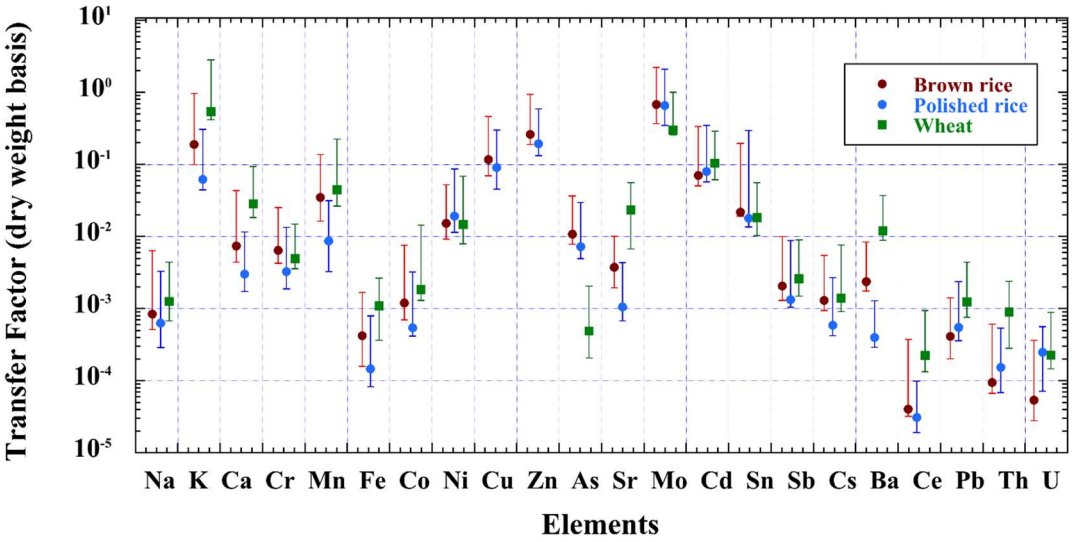

FIG. XV-2. Geometric means of TFs (DM basis) for brown rice, polished rice and husked wheat. Both ends of bar show maximum and minimum TF values.

A simple extraction method was applied to measure stable iodine in plant samples by ICP-MS [XV-18]. In brief, about 100 mg of dried sample were weighed into a 6 mL PFA vessel (026R, Savillex Co.). Then, 1 mL of super-pure grade 25% tetramethyl ammonium hydroxide (TMAH, TAMAPURE-AA-100, Tama Chemicals Co. Ltd.), was added. The vessel was closed tightly and was heated overnight (about 12 h) at 60 ◦C. The sample in the vessel was diluted to 50 mL with deionised water and centrifuged to obtain supernatant which contained about 0.5% TMAH for iodine measurement by ICP-MS. The method can successfully recover ca. 100% of I from plant samples [XV-18]. For soil samples, energy dispersive X-ray fluorescence (Epsilon 5, PANalytical B. V.) was used [XV-19].

XV-2.2.2. Transfer factors of indigenous elements

Figure XV-2 shows the cereal TF values (geometric mean: GM) for 25 elements [XV-17, XV-20]. Some elements had TF values that were higher than 0.1: K, Cu, Zn and Mo for brown rice; Zn and Mo for polished rice and K, Mo and Cd for wheat. The TF values of Th and U for brown rice were 1.0×10^{-4} and 5.0×10^{-5}; those for polished rice were 1.5×10^{-4} and 2.0×10^{-4}; and those for husked wheat were 9.0×10^{-4} and 2.0×10^{-4}, respectively. Except for several trace elements, TF values were usually highest in wheat followed by brown rice and then polished rice.

Previous TF values for ^{137}Cs and ^{90}Sr in brown rice, polished rice and husked wheat [XV-21–XV-23] were summarized by Uchida et al. [XV-24]; thus, the obtained TF values of stable Cs and Sr were compared with those of ^{137}Cs and ^{90}Sr. The GMs of TF for ^{137}Cs were 2.6×10^{-3} (brown rice) and 1.1×10^{-3} (polished rice) in the samples collected in 1999 while those of stable Cs were 1.3×10^{-3} (brown rice) and 7.0×10^{-4} (polished rice). The GMs of TFs for ^{90}Sr were 1.5×10^{-2} for brown rice and 5.9×10^{-3} for polished rice, while those for stable Sr were $3.8 \times 10\text{-}^{3}$ for brown rice and 1.3×10^{-3} for polished rice. From these results, apparently, these two elements were associated mostly with the rice bran. It should be noted that the values were close to each other, but the TFs of ^{137}Cs and ^{90}Sr were usually higher than those of stable Cs and Sr. Tsukada et al., [XV-25] also reported that TF-^{137}Cs was approximately 3 times higher than TF-Cs. The phenomena could be explained as follows; fallout ^{137}Cs and ^{90}Sr were more bioavailable to plants than stable Cs and Sr in the soil for a certain period of time. Some of the

stable Cs and Sr are found in soil mineral structures that ^{137}Cs and ^{90}Sr cannot easily enter, so that these stable and radioactive isotopes have not reached an equilibrium condition. However, after a long time period, ^{137}Cs and stable Cs and ^{90}Sr and stable Sr have reached an approximately isotopic equilibrium in the bioavailable fraction in the soils, therefore, the TF of stable Cs and Sr can be used for long-term transfer of ^{137}Cs and ^{90}Sr in the environment [XV-26].

The GM of TFs for ^{137}Cs and ^{90}Sr in husked wheat were 2.9×10^{-3} and 8.3×10^{-2}, respectively, and those of stable Cs and Sr were 1.6×10^{-3} and 2.2×10^{-2}, respectively [XV-24]. The IAEA [XV-2] reported expected TF values for cereals collected in a temperate climate; the TF-Cs and TF-Sr were 1.0×10^{-2}–8.3×10^{-2} and 2.0×10^{-2}–2.1×10^{-1}, respectively. Both expected values were slightly higher than the TFs of ^{137}Cs, ^{90}Sr, stable-Cs and -Sr we obtained in Japan. Probably, climates, soil types and vegetation influence the parameters. Although our data are limited, further study is necessary to collect local TF values for precise radiological assessment.

XV-2.2.3. Transfer factors of iodine

Using the 148 data sets, we calculated TF values of stable iodine [XV-27]. The results are shown in Table XV-3. The GM value of the TFs for fruit vegetables and leafy vegetables, 1.4×10^{-2}, was the highest among the crops, while the lowest value of 3.9×10^{-3} was obtained for brown rice. The TFs for brown rice were within the previously reported values, 1.5×10^{-4} to 3.9×10^{-2} [XV-5, XV-28, XV-29]. The TFs of iodine for the white part of leeks were within the range of leafy vegetables, however, the GM value was much closer to that of root crops. The GMs of tubers and fruit vegetables compiled by the IAEA [XV-25] were, however, 1–2 orders of magnitude higher. The GM value of TFs of iodine for wheat and barley were about 8 times higher than that for cereals compiled by the IAEA, which may be due to greater iodine mobility in the Japanese agricultural soil samples.

XV-3. SOIL-SOIL SOLUTION DISTRIBUTION COEFFICIENT (K_D)

The soil-solution distribution coefficient, K_d, (L/kg) is defined using the following equation:

$$K_d = \frac{(C_i - C_e)}{C} \times \frac{W_l}{W_s} \qquad \text{(XV-2)}$$

where C_i (Bq/L) is the initial radionuclide activity, C_e (Bq/L) is the radionuclide activity in the liquid phase after shaking for 7 days with the tracer, W_l is the solution volume (L), and W_s is the soil dry weight (kg DM).

XV-3.1. Sorption experiments of radionuclides on soils

XV-3.1.1. Materials and methods

The one hundred and forty-two agricultural soil samples (63 paddy soil and 79 upland soil samples) for TF determination in Section XV-2.2 were also used for K_d evaluation. Some soil properties, such as pH, electrical conductivity (EC) and cation exchange capacity (CEC) were measured.

The distribution coefficient (K_d) is often used to predict the behavior of a radionuclide in soil-soil water systems. This coefficient is defined as the concentration of a radionuclide per unit weight of soil divided by concentration of a nuclide per unit volume of solution, at equilibrium of the system.

TABLE XV-3. SOIL TO CROP (EDIBLE PART, DM) TRANSFER FACTORS OF IODINE [XV-27]

Crop parts	Number of data	TF of Iodine		
		Minim	Geometric mean	Maxim
Leafy vegetables	22	9.8×10^{-4}	1.4×10^{-2}	4.9×10^{-1}
Leek (white part)	4	1.3×10^{-3}	4.0×10^{-3}	8.4×10^{-3}
Root crops	14	8.7×10^{-4}	6.1×10^{-3}	6.7×10^{-2}
Tubers	11	9.4×10^{-4}	6.9×10^{-3}	9.4×10^{-2}
Fruit vegetables	18	1.6×10^{-3}	1.4×10^{-2}	1.4×10^{-1}
Legumes	7	6.3×10^{-4}	4.7×10^{-3}	4.2×10^{-2}
Wheat and barley	9	5.1×10^{-4}	4.9×10^{-3}	3.0×10^{-2}
Brown rice	59	4.5×10^{-4}	3.9×10^{-3}	1.8×10^{-2}
Bran	63	3.3×10^{-3}	3.1×10^{-2}	1.6×10^{-1}
Polished rice	45	3.5×10^{-4}	2.1×10^{-3}	4.9×10^{-3}

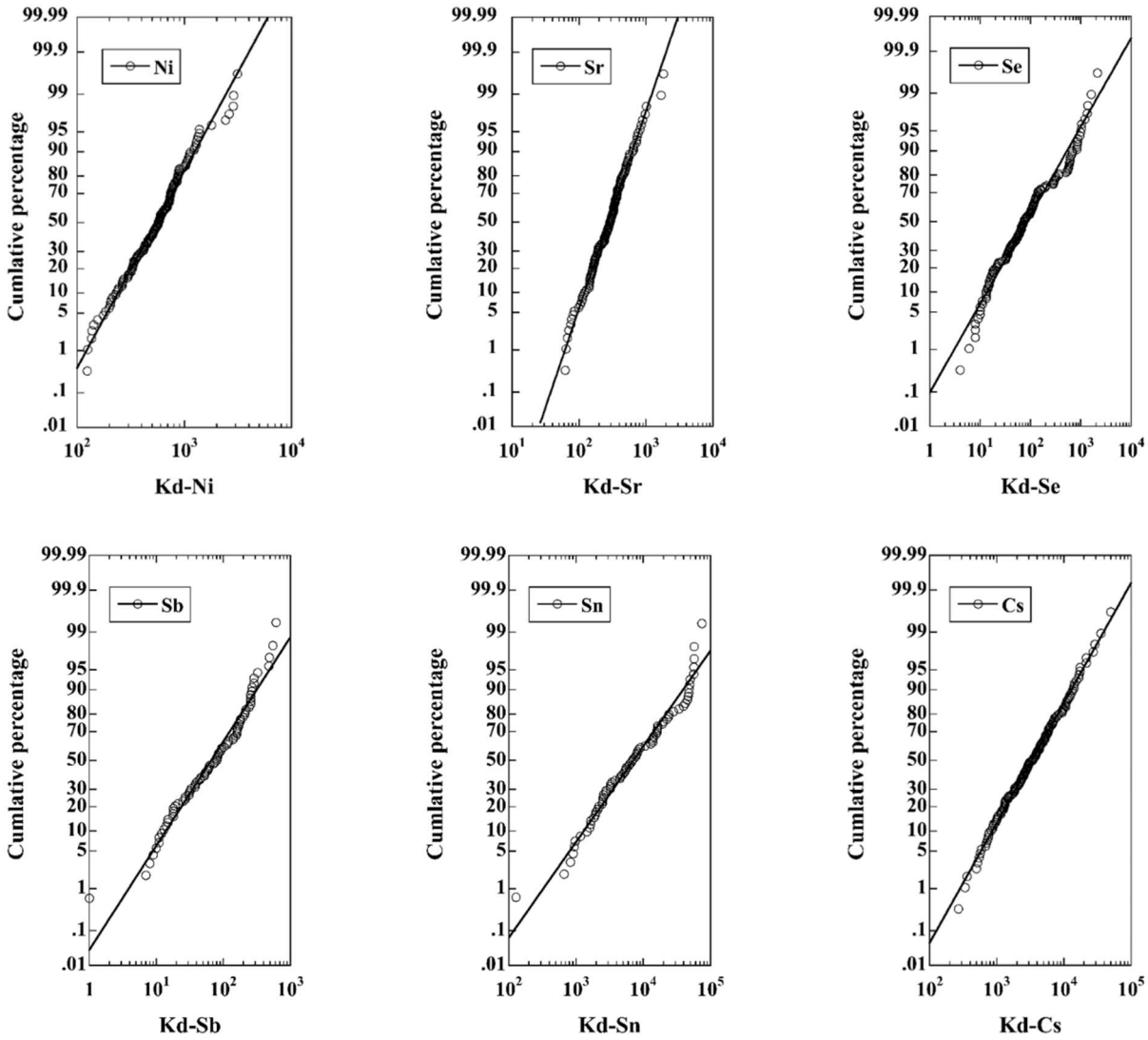

FIG. XV-3. Probability distributions of K_d values of ^{63}Ni, ^{75}Se, ^{85}Sr, ^{113}Sn, ^{124}Sb and ^{137}Cs for Japanese agricultural soils.

The K_d of the five radionuclides were obtained by separate batch sorption tests. Each soil sample and deionized water (solid:liquid ratio, 1 g: 10 mL) were mixed in a plastic bottle, and initially shaken for 24 h at 23°C, and then one radionuclide (^{63}Ni, ^{75}Se, ^{85}Sr, ^{113}Sn, ^{124}Sb, or ^{137}Cs) was added as a tracer. After shaking for 7 days, the suspension was centrifuged at 3000 rpm for 10 minutes, and the supernatant was filtered through a 0.45-µm membrane filter. Radioactivity of the radionuclide in the filtrate was measured with a NaI scintillation counter; for ^{63}Ni, a liquid scintillation counter was used.

XV-3.1.2. K_d values of radionuclides in Japanese agricultural soils

Statistical characteristics of K_d values

The distribution of the measured K_d values [XV-30–XV-35] are shown in Fig. XV-3. From the Shapiro-Wilk test, the K_d data distributions for ^{63}Ni, ^{85}Sr, ^{113}Sn, and ^{137}Cs were judged as not a normal type ($p < 0.05$), but a log-normal type. For ^{75}Se and ^{124}Sb, their K_d distributions were not a normal or a log-normal type ($p < 0.05$).

Some statistical characteristics of K_d values are shown in Table XV-4. The variation of K_d values is up to two or three orders of magnitude. Their geometric means were: 6.9×10^2 L/kg for Ni; 8.5×10^1 L/kg for Se; 2.8×10^2 L/kg for Sr; 7.2×10^3 L/kg for Sn; 6.6×10^1 L/kg for Sb; and 3.2×10^3 L/kg for Cs.

In comparison with the expected K_d values for loam soil type reported by IAEA TRS 472 [XV-3], the present results are more than three times higher than the literature values for Sr (expected value: 5.2×10^1 L/kg) and Sn (expected value: 1.6×10^3 L/kg), and similar (differences within three folder) for Ni (expected value: 2.8×10^2 L/kg), Se (expected value: 2.0×10^2 L/kg), Sb (expected value: 6.2×10^1 L/kg) and Cs (expected value: 1.2×10^3 L/kg). The K_d values for Se, Sr, and Cs differ significantly between paddy and upland soil samples in *t*-test ($p < 0.05$), but Sn and Sb do not.

XV-3.1.3. Correlations between K_d values and soil properties

Spearman's rank correlation test was used for evaluating correlations between K_d values and soil properties. Good correlations (Spearman's rank correlation coefficient (R_s) > |0.5|) are found in the following combinations:

Se-K_d – Water soluble P (R_s = -0.51)
Sr-K_d – Electric conductivity (R_s = -0.52)
Sr-K_d – Water soluble Ca (R_s = -0.57)
Sn-K_d – Electric conductivity (R_s = -0.50)
Sn-K_d – Water soluble Ca (R_s = 0.50)
Sn-K_d – water soluble Mg (R_s = 0.54)
Sn-K_d – Water soluble Sr (R_s = 0.57)
Sb-K_d – pH (R_s = -0.54)
Sb-K_d – Acid oxalate extractable Fe (R_s = 0.58)
Sb-K_d – Water soluble P (R_s = -0.67)

In Japanese agricultural soils, Se and Sb are probably present as oxyanion forms, i.e. $HSeO_3^-$ and SbO_3^-, respectively [XV-30, XV-31]. Phosphate could be present as $H_2PO_4^-$ under pH and Eh conditions in Japanese agricultural soils [XV-36]. Thus, negative correlations between K_d values of Se or Sb and water-soluble P can be attributed to competition by $HSeO_3^-$ and SbO_3^- for $H_2PO_4^-$ because these three ions can sorb on the same sorption sites in soils.

TABLE XV-4. STATISTICAL CHARACTERISTICS OF K_D (L/KG) VALUES

Soil use		Ni	Se	Sr	Sn	Sb	Cs
All	GM [a]	5.5×10^2	8.5×10^1	2.8×10^2	7.2×10^3	6.6×10^1	3.2×10^3
Paddy	n	63	63	63	37	36	62
	GM	6.9×10^2	1.2×10^2	3.7×10^2	5.5×10^3	7.8×10^1	2.4×10^3
	Min	2.0×10^2	1.0×10^1	9.9×10^1	6.6×10^2	1.1×10^1	2.7×10^2
	Max	3.1×10^3	2.1×10^3	1.8×10^3	5.6×10^4	6.1×10^2	2.9×10^4
Upland	n	79	79	79	40	45	79
	GM	4.5×10^2	6.7×10^1	2.2×10^2	9.1×10^3	5.8×10^1	4.1×10^3
	Min	1.1×10^2	4.0×10^0	6.2×10^1	1.3×10^2	1.0×10^0	3.6×10^2
	Max	1.8×10^3	1.4×10^3	6.4×10^2	7.4×10^4	5.5×10^2	3.6×10^4

[a] GM: Geometric Mean.

In upland soil samples, good correlations are found between the Se-K_d values and acid oxalate extractable Al or Fe with R_ss of 0.57 and 0.62, respectively ($p < 0.01$). Selenite is known to be able to associate with aluminium and iron in soil [XV-37]. Since upland soil samples included 29 Andosol samples which have one order of magnitude higher acid oxalate extractable Al and Fe concentrations than other soil groups do, good correlation coefficients are obtained for upland soil samples but not paddy soil samples.

It is reasonable that Sr- K_d values have good correlations with EC and water soluble Ca for the following two reasons: one is that the sorption mechanism of Sr in soil is cation exchange and the other is that Sr has similar chemical characteristics to Ca.

As described above, Se and Sb have similar sorption behaviors in Japanese agricultural soils. Therefore, the same reason for Se, that is, Sb would be able to associate with aluminum and iron in soil may be applicable to the good correlation between Sb- K_d values and acid oxalate extractable Fe. For Sn, only a few research studies about its sorption in soil have been carried out [XV-33]. In addition, there are no reports on the relationship between Ca, Mg, or Sr and Sn in soils. Further studies are needed to clarify the reasons for the good correlations between these water-soluble elements and Sn-K_d values.

No soil properties have a good correlation with Cs-K_d values in all types of soil samples. However, in upland soil samples, Cs-K_d values have quite a good correlation with water soluble ammonium (NH_4^+) with R_s = -0.48 and water-soluble rubidium (Rb) with R_s = -0.45. Some types of clay minerals such as illite have specific sorption sites for Cs^+, NH_4^+, Rb^+, and K^+ based on their ionic radius. This fact supports the good correlations between Cs-K_d values and water soluble NH_4^+ or water soluble Rb.

Yasuda et. al. reported that K_d for Cs, Sr, Co and Zn showed a lognormal distribution [XV-39] and the K_d of strontium showed an adequate correlation with the value of the CEC divided by the supernatant EC [XV-40].

XV-4. DECONTAMINATION OF RADIONUCLIDES BY FOOD PROCESSING

The food processing retention factor (F_r) provides the fraction of the total activity of radionuclides in the raw product retained in the food after processing (Bq processed food per Bq raw product):

$$F_r = \frac{A_{pf}}{A_{rf}} \quad \text{(XV-3)}$$

where A_{pf} is the total activity of processed food, Bq and A_{rf} is the total activity of raw material. F_r can be calculated using the following equation as reported in IAEA TRS 472 [XV-3]:

$$F_r = P_f \times P_e \quad \text{(XV-4)}$$

where P_f is the ratio of the element activity concentrations and P_e is the ratio of the raw weight of the processed food to the weight of the original raw material.

The retention fraction varies with the uptake route and chemical form of the nuclides administered.

XV-4.1. Removal of radionuclides from leafy vegetables during washing and boiling

Before the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, removal rates of radionuclides during washing and boiling of leafy vegetables using internal contaminated samples (root uptake) were studied [XV-41]. The results are listed in Table XV-5. F_r data for Mn, Co, and Zn were not provided in IAEA TRS 472 [XV-3]; for Sr, Cs and I, the F_r values comparable to the listed food processing generally agreed with IAEA TRS 472.

When a nuclear accident occurs, leafy vegetables are expected to be contaminated with radioiodine (methyliodide and elemental iodine) deposited from the atmosphere. The results of the laboratory experiments using spinach exposed to air which contained elemental iodine (I_2) or methyliodide (CH_3I) forms are shown in Fig. XV-4(A) [XV-42]. The percentages of their removal by boiling were 33% and 58%, respectively. This suggests that I_2 might combine more tightly with the leaf constituents.

The removal of ^{131}I from vegetables containing radionuclides from the Chernobyl fallout using these procedures [XV-43, XV-44] are shown in Fig. XV-4(B).

About 10% of ^{131}I was removed by gentle washing with water in a beaker for 5 minutes. The removal rate of ^{131}I by washing and/or boiling may depend on the amount of ^{131}I combined with dust on leaves, which is easily washed out. About 70% of the ^{131}I was removed by boiling in slightly salted water for 5 min. The percentage removal by boiling for the samples containing radionuclides of Chernobyl origin ^{131}I was comparable to the values for samples exposed to CH_3I. This was agreed with the findings by Noguchi and Murata [XV-45] that the gaseous ^{131}I from Chernobyl was mainly an organic form (e.g. CH_3I).

TABLE XV-5. FOOD PROCESSING RETENTION FACTOR FOR LEAFY VEGETABLES

Radionuclide	Crop name	F_r Washing	F_r Boiling	F_r Washing-Boiling
^{54}Mn	Spinach	0.97	0.44	0.42
	Komatsuna	0.95	0.63	0.60
^{60}Co	Spinach	1.00	0.28	0.28
	Komatsuna	0.90	0.33	0.30
^{65}Zn	Spinach	0.95	0.63	0.60
	Komatsuna	0.95	0.76	0.72
^{85}Sr	Spinach	0.95	0.71	0.68
	Komatsuna	0.95	0.53	0.50
^{137}Cs	Spinach	0.85	0.08	0.07
	Komatsuna	0.90	0.11	0.10
^{131}I	Spinach	1.00	0.30	0.30
	Komatsuna	0.95	0.18	0.17

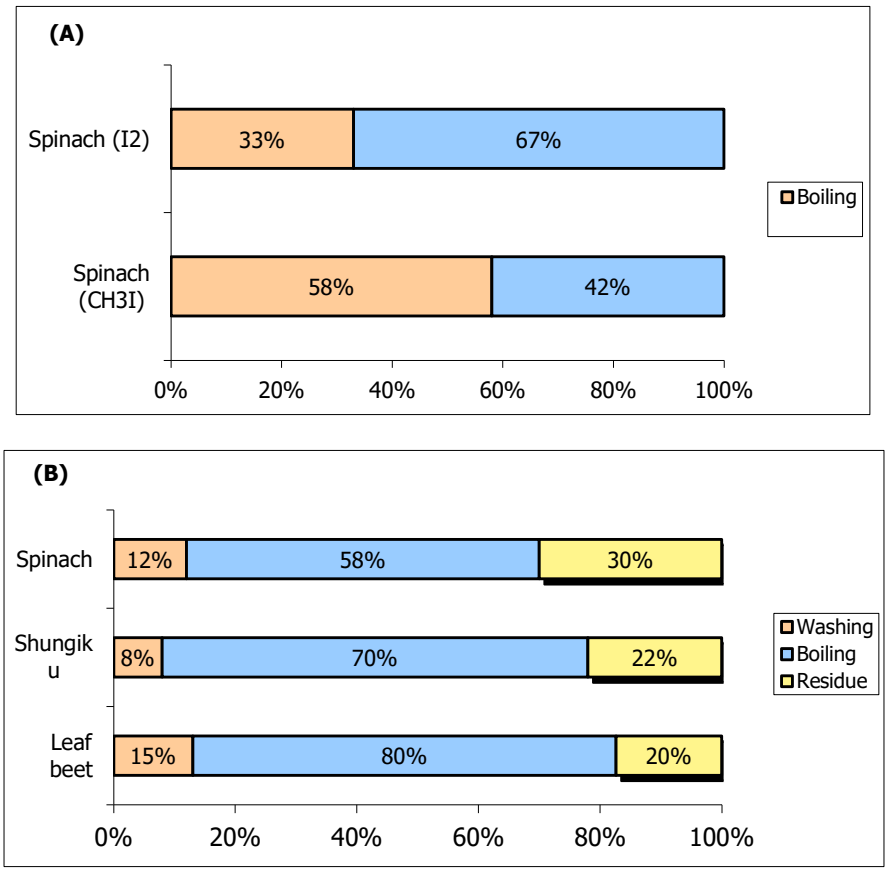

FIG. XV-4. Removal of iodine from vegetables by washing and/or boiling. Samples contaminated in laboratory experiments (A) or by Chernobyl fallout (B). Shungiku (Chrysanthemum coronarium) is an edible chrysanthemum.

XV-4.2. Removal of radiocaesium from foods during culinary preparation observed after the Fukushima nuclear accident

XV-4.2.1. F_r values of radiocaesium for rice

After the FDNPP accident, decontamination of radiocaesium by food processing for paddy rice, root crops (turnip and radish), fruits (persimmon, apple and loquat) and nuts (chestnut and peanut) were collected by measuring ^{134}Cs and ^{137}Cs using Ge detecting systems (Seiko EG&G). Raw materials were mainly collected from our institute fields in Chiba Prefecture and some sites in Fukushima Prefecture. Information on sampling sites and processing methods has been reported elsewhere [XV-46–XV-48].

The F_r cannot exceed unity if a raw sample for radioactivity measurement is directly used for food processing. However, in this study, most raw samples had low radiocaesium concentrations, so we separated each collected sample into three portions, i.e. raw, washed, and washed+processed samples to obtain concentrated samples after drying, separately. Thus, F_r sometimes exceeded unity. Both ^{134}Cs and ^{137}Cs data were obtained and the average value for each sample was reported.

Polished rice is generally consumed in Japan; however, food monitoring has been carried out on a brown rice basis. It is well known that Cs concentration is high in rice bran [XV-20, XV-49]. Previously, F_r values were obtained for rice samples collected in Fukushima Prefecture

in 2011 after polishing and washing the rice [XV-46], and the results are summarized in Table XV-6. In Japan, traditional rice cooking method is absorption method with boiling and polished rice usually used after washing and soaking. The polishing rate from brown rice to polished rice is 90-92%; that is the P_e value is 0.90–0.92. The concentration ratio P_f observed was 0.49 on average (range: 0.46–0.52) and thus the average F_r value was 0.45 (range: 0.42–0.47).

According to food processing related parameter report [XV-50] that compiles radionuclide removal rates by food processing and includes Japanese data, the Cs removal rate by polishing to polished rice was 57-80% with 65% on average, which means that the F_r value was 0.35. When polished rice was washed, the F_r value was 0.56 on average.

XV-4.2.2. F_r values of radiocaesium for vegetables

The data obtained in NIRS [XV-47, XV-48, XV-51] after the FDNPP accident are summarized in Table XV-7. The F_r, as well as P_e are listed for washing, washing and boiling, pickling and peeling of different types of vegetables.

When the results for leafy vegetables contaminated indirectly or directly were compared for both washing and boiling, F_r values were usually small for directly contaminated samples. For example, by washing, the average F_r for indirect contaminated leafy vegetables was 0.92 and that for directly contaminated leafy vegetables was 0.75. The F_r values by washing for indirectly contaminated leafy vegetables agreed well with pre-accident tracer study as shown in Table XV-5. By washing + boiling for 2.5 min., average F_r for indirectly contaminated leafy vegetables was 0.55 and that for directly contaminated leafy vegetables was 0.35. The differences between direct and indirect contamination pathways were possibly because surface contamination was easy to remove by both methods.

For pickling, ion exchange of Cs^+ and K^+ by Na^+ would occur, thus, Cs concentrations decreased. However, it was difficult to remove all radiocaesium with this process. According to the data compiled by Kashparov et al. [XV-52], F_r values ranged 0.1–1; the efficiency of radionuclide removal through the process varies widely, however, from the results in Table XV-7, it was concluded that ion exchange is one of the more effective processing methods to remove radiocaesium. When salt is used, Na is the only cation that can replace Cs and K. However, for pickling with soy sauce, which contains ca. 60 g/kg of Na and ca. 3.5 g/kg of K, F_r differences between K and radioactive Cs might be found.

Potassium can be used as an analogue to estimate radiocaesium F_r by food processing of vegetables for the case of indirect contamination pathway [XV-47]. However, for some tissues, distributions of K and Cs in a plant are not the same [XV-53]. Hence, K would provide a supportive data although K is not a perfect analogue of Cs in food processing.

TABLE XV-6. FOOD PROCESSING EFFICIENCY (P_E), FOOD CONCENTRATION RATIO (P_F) AND FOOD PROCESSING RETENTION FACTOR (F_R) OF RADIOCAESIUM FOR RICE (AVERAGE)

Process	Material	P_e	P_f	F_r
Polishing	Brown rice	0.92	0.49	0.45
Washing	Brown rice	0.99	0.94	0.93
Washing	Polished rice	0.96	0.59	0.56

TABLE XV-7. FOOD PROCESSING EFFICIENCY (P_E), AND FOOD PROCESSING RETENTION FACTOR (FR) OF RADIOCAESIUM FOR VEGETABLES

Sample	Contamination pathway	Process	N	P_e (Range)	F_r (Range)	Ref.
Leafy vegetables	Indirect	Washing	14	1.0	0.92 (0.27–1.2)	[XV-47]
Leafy vegetables	Direct	Washing	8	1.0	0.75 (0.49–1.2)	[XV-48]
Turnip	Indirect	Washing	1	1.0	0.48	[XV-51]
Bamboo shoot	Indirect	Washing + 10-15 min. Boiling	4	1.0	0.70 (0.67–0.74)	[XV-47]
Leafy vegetables	Indirect	Washing + 2.5 min. Boiling	22	0.96 (0.83–1.1)	0.55 (0.22–0.93)	[XV-47]
Leafy vegetables	Direct	Washing + 2.5 min. Boiling	6	0.96 (0.77–1.1)	0.35 (0.15–0.58)	[XV-48]
Turnip	Indirect	Washing + 2.5 min. Boiling	1	0.94	0.82	[XV-51]
Garlic	Indirect	Pickling in soy sauce, 2 months	1	0.93	0.38	[XV-47]
Someiyoshino Cherry leaves	Indirect	Pickling in salt, 3-5 days	2	Not measured	0.18 (0.13–0.22)	[XV-47]
Turnip	Indirect	Pickling in 9% (w/w) salt, 14 h	2	0.75 (0.61–0.73)	0.49 (0.32–0.65)	[XV-51]
Japanese radish	Indirect	Peeling	1	0.89	0.16	[XV-51]

XV-5. LITERATURE REVIEW

XV-5.1. Transfer factors of ^{90}Sr, ^{137}Cs, ^{239,240}Pu and iodine

The National Institute of Agro-Environmental Sciences in Japan has measured the concentrations of fallout ^{90}Sr and ^{137}Cs in brown rice, wheat and farm soil samples collected from various parts of Japan. Komamura and Tsumura [XV-54] calculated the TF of radionuclides and stable elements from paddy soil to polished rice using the ^{90}Sr and ^{137}Cs survey data and analytical data obtained by conventional radiometric and ICP-MS methods. The results are shown in Table XV-8. The TF of fallout ^{90}Sr and ^{137}Cs were 4 to 6 times higher than those of stable strontium and caesium.

Table XV-9 shows the concentrations of ^{137}Cs in husked wheat and upland soils and their TF. The average TF was about 6.0×10^{-3} [XV-55]. The range of the TF of ^{137}Cs was within one order of magnitude of those for wheat.

Okajima et al. [XV-56] reported the TF of ^{239,240}Pu in Nishiyama, Nagasaki City, where there was radioactive fallout concentrated as black rain following the atomic bombing on the city. As this bomb was a plutonium bomb, the fallout must have contained non-fission ^{239}Pu in addition to fission products. In 1982 and 1983, cultivated soils and plants were collected in this area. The TF of ^{239,240}Pu and ^{137}Cs to six kinds of plants are shown in Table XV-10. Control samples were collected from outside Nishiyama where non-fission plutonium is absent. The TF for ^{239,240}Pu were of the order of 1.0×10^{-4} to 1.0×10^{-3}; those from the Nishiyama district were lower than those from the control district. For ^{137}Cs, the TF ranged from 3.0×10^{-2} to 2.1×10^{-1} for the Nishiyama district and from 1.0×10^{-2} to 1.5×10^{-1} for the control area. The TF of ^{137}Cs were 100 to 200 times higher than those of plutonium obtained in Nishiyama.

Takagi et al. [XV-57] analyzed stable iodine concentrations in rice and paddy soil in Japan and estimated the TF in brown rice and polished rice. The results are shown in Table XV-11. The TF for polished rice ranged from 1.0×10^{-4} to 8.0×10^{-3}, while TF for brown rice ranged from 5.9×10^{-4} to 2.0×10^{-3}.

Namiki et al. [XV-58] also collected 27 samples, each a pair of polished rice and a paddy soil, around Tokai Village. They estimated that the transfer factor of iodine to polished rice was 1.5×10^{-3}. Although the species of rice plant, soil types and experimental conditions were different, the values obtained in these studies and our experiments described above were similar.

XV-5.2. Distribution coefficients (K_d)

The K_ds for each nuclide showed a lognormal distribution except for ^{54}Mn [XV-39]. When the correlation between K_ds and soil properties was studied, Mn and Co appear to be highly correlated with the exchangeable Ca; Zn with the water content; Sr with the cation exchange capacity; and Cs with the exchangeable K. Only the K_d of Sr showed an adequate correlation with the value of the CEC divided by the supernatant EC [XV-40]. The variation of K_d (L/kg) was up to two or three orders of magnitude and GMs of K_d measured were 1.8×10^2 for Co and Cs, 2.0×10^3 for Zn and 1.7×10^2 for Sr [XV-39].

Table XV-12 shows the distribution coefficients of radionuclides for soils obtained in Japan and other countries [XV-59]. The data were collected from publications, mainly from 1980 to 1989. The Japanese data were mainly obtained in laboratories, while the data from other countries were obtained in actual outdoor environments. There were no systematic differences in K_d values between Japan and the other countries although the variations are large. K_d values of radionuclides on clay were higher than those on sand and loam. A K_d value of a radionuclide depends not only on the size of the soil particles (surface area per unit weight), but also on the types of minerals and organic matters in the soils. However, it is useful for prediction of radionuclide migration in soil to give K_d values for categorized soil types.

XV-5.3. Food processing retention factors in leafy vegetables

Hisamatsu et al. [XV-60] reported the retention factors of ^{131}I, ^{103}Ru, ^{134}Cs and ^{137}Cs of Chernobyl origin in leafy vegetables due to cooking. Samples were obtained in Akita City, Japan. Retention factors in boiled vegetables with respect to unwashed vegetables are shown in Table XV-13. The overall decontamination ratio of ^{131}I was calculated at 0.42 ± 0.19 which suggests that most ^{131}I is not present in particles adhering to the surface of leaves. Approximately half the ^{103}Ru in vegetables was removed as a result of washing and boiling. The retention factors for ^{134}Cs and ^{137}Cs were similar; the caesium content in boiled vegetables was 34% of that in unwashed vegetables.

TABLE XV-8. TRANSFER FACTORS OF SELECTED ELEMENTS FROM PADDY SOIL TO POLISHED RICE IN JAPAN [XV-54]

Element / Radionuclide	N	TF	Element / Radionuclide	N	TF
K	15	$8.9 \times 10^{-2} \pm 5.8 \times 10^{-2}$	La	5	$1.5 \times 10^{-4} \pm 1.0 \times 10^{-4}$
K-40	15	$1.0 \times 10^{-1} \pm 7.5 \times 10^{-2}$	Ce	14	$4.5 \times 10^{-5} \pm 4.5 \times 10^{-5}$
Ca	15	$5.8 \times 10^{-3} \pm 2.7 \times 10^{-3}$	Sm	14	$6.6 \times 10^{-5} \pm 3.2 \times 10^{-5}$
Rb	14	$3.3 \times 10^{-2} \pm 2.3 \times 10^{-2}$	Eu	14	$5.8 \times 10^{-4} \pm 3.0 \times 10^{-4}$
Sr	14	$7.4 \times 10^{-4} \pm 2.7 \times 10^{-4}$	Gd	14	$5.7 \times 10^{-5} \pm 2.7 \times 10^{-5}$
Sr-90	14	$4.8 \times 10^{-3} \pm 3.4 \times 10^{-3}$	Lu	14	$8.8 \times 10^{-5} \pm 3.1 \times 10^{-5}$
Cs	14	$7.8 \times 10^{-4} \pm 6.9 \times 10^{-4}$	Bi	14	$2.2 \times 10^{-4} \pm 2.1 \times 10^{-4}$
Cs-137	15	$2.6 \times 10^{-3} \pm 2.8 \times 10^{-3}$	Th	11	$1.5 \times 10^{-4} \pm 1.7 \times 10^{-4}$
Ba	14	$5.0 \times 10^{-4} \pm 6.3 \times 10^{-4}$	U	11	$1.9 \times 10^{-4} \pm 1.2 \times 10^{-4}$

TABLE XV-9. CONCENTRATIONS OF FALLOUT CS-137 IN HUSKED WHEAT AND UPLAND SOILS IN 1988 AND TRANSFER FACTORS [XV-55]

Location	Activity concentration (Bq/kg DM)		TF
	Husked wheat	Upland soil	
Hokkaido	0.131	11.4	1.1×10^{-2}
Iwate	0.076	17.8	4.3×10^{-3}
Miyagi	0.051	10.4	4.9×10^{-3}
Niigata	0.059	28.8	2.0×10^{-3}
Ibaraki	0.075	5.2	1.4×10^{-2}
Saitama	0.036	6.4	5.6×10^{-3}
Tokyo	0.034	13.1	2.6×10^{-3}
Okayama	0.023	9.5	2.4×10^{-3}
Average (AM ± SD)	0.061 ± 0.032	12.8 ± 7.1	$6.0 \times 10^{-3} \pm 4.3 \times 10^{-3}$

TABLE XV-10. TRANSFER FACTORS OF CS-137 AND PU-239+240 FROM SOIL TO VEGETABLES IN JAPAN [XV-56]

Vegetable	TF (on a DM basis)			
	Cs-137		Pu-239+240	
	Nishiyama	Control	Nishiyama	Control
White potato	1.5×10^{-1}	4.6×10^{-2}	7.2×10^{-4}	4.8×10^{-3}
Sweet potato	1.3×10^{-1}	1.0×10^{-2}	1.4×10^{-3}	3.7×10^{-3}
Pumpkin	1.1×10^{-1}	6.5×10^{-2}	4.3×10^{-4}	1.2×10^{-3}
Taro	5.9×10^{-2}	2.7×10^{-2}	6.2×10^{-4}	8.6×10^{-4}
Radish	2.1×10^{-1}	1.5×10^{-1}	5.3×10^{-4}	8.6×10^{-3}
Leaf mustard	3.3×10^{-2}	4.0×10^{-2}	1.9×10^{-4}	2.0×10^{-3}

TABLE XV-11. CONCENTRATIONS OF STABLE IODINE AND TRANSFER FACTORS IN HULLED RICE, POLISHED RICE, PADDY SOILS [XV-57]

Location	Concentration of stable iodine					Transfer factor		
	Rice (μg/kg DM)			Soil (mg/kg DM)				
	1979 Polished rice	1980 Polished rice	1980 Brown rice	1979	1980	1979 Polished rice	1980 Polished rice	1980 Brown rice
Hokkaido	1.8 ± 0.7	3.0 ± 0.8	10.6 ± 1.3	1.86 ± 0.08	2.46 ± 0.09	9.7×10^{-4}	1.2×10^{-3}	4.3×10^{-3}
Akita	2.2 ± 0.7	4.6 ± 1.2	12.2 ± 1.3	1.58 ± 0.06	1.29 ± 0.08	1.4×10^{-3}	3.6×10^{-3}	9.5×10^{-3}
Niigata	2.3 ± 0.6	3.7 ± 0.7	10.4 ± 1.2	1.15 ± 0.05	1.4 ± 0.07	2.0×10^{-3}	2.6×10^{-3}	7.4×10^{-3}
Ishikawa	1.6 ± 0.6	— [a]	—	0.6 ± 0.04	0.61 ± 0.05	2.7×10^{-3}	–	–
Tottori	2.2 ± 0.8	4.6 ± 0.7	5.9 ± 1.2	0.98 ± 0.04	1.27 ± 0.08	2.2×10^{-3}	3.6×10^{-3}	4.6×10^{-3}
Iwate	2.1 ± 0.7	3.6 ± 1.1	9.4 ± 1.3	10.2 ± 0.3	9.47 ± 0.25	2.1×10^{-4}	3.8×10^{-4}	9.9×10^{-4}
Miyagi	2.7 ± 0.6	3.8 ± 0.8	7.7 ± 1.0	2.33 ± 0.1	2.11 ± 0.12	1.2×10^{-3}	1.8×10^{-3}	3.6×10^{-3}
Ibaraki	2.4 ± 0.6	2.5 ± 0.8	10.1 ± 1.0	19.2 ± 0.3	17.2 ± 0.3	1.3×10^{-4}	1.5×10^{-4}	5.9×10^{-4}
Saitama	1.9 ± 0.6	5.0 ± 0.8	7.7 ± 1.0	0.95 ± 0.04	0.95 ± 0.04	2.0×10^{-3}	5.3×10^{-3}	8.1×10^{-3}
Tokyo	2.5 ± 0.7	4.2 ± 0.7	4.7 ± 1.0	1.29 ± 0.07	1.35 ± 0.07	1.9×10^{-3}	3.1×10^{-3}	3.5×10^{-3}
Yamanashi	3.2 ± 0.7	2.9 ± 0.8	4.1 ± 1.0	0.41 ± 0.04	0.39 ± 0.06	7.8×10^{-3}	7.4×10^{-3}	1.1×10^{-2}
Osaka	2.7 ± 0.7	2.5 ± 0.6	12.2 ± 1.3	0.54 ± 0.04	0.62 ± 0.05	5.0×10^{-3}	4.0×10^{-3}	2.0×10^{-2}
Okayama	4.0 ± 0.7	4.7 ± 0.7	4.9 ± 1.2	0.61 ± 0.66	0.81 ± 0.06	6.6×10^{-3}	5.8×10^{-3}	6.0×10^{-3}
Fukuoka	2.9 ± 0.7	3.8 ± 1.1	6.9 ± 1.2	0.86 ± 0.06	0.61 ± 0.04	3.4×10^{-3}	6.2×10^{-3}	1.1×10^{-2}

[a] —: Data not available.

TABLE XV-12. DISTRIBUTION COEFFICIENTS (K_D) FOR VARIOUS SOILS IN JAPAN AND IN OTHER COUNTRIES [XV-59]

Element	Distribution coefficient (K_d, L/kg)					
	Japan			Other countries		
	Sand	Loam	Clay	Sand	Loam	Clay
Co	3–1000	10–3300	20–12 000	100–4800	—	2–12 000
Sr	50–680	0.5–2700	10–9000	0.3–170	0.9–150	1–100 000
I	40	— [a]	—	—	—	0.5–1500
Cs	3–8000	1–2500	50–70 000	6–3800	—	0.4–110 000
U	4600	—	—	0.1–2200	2–73	2–650
Pu	970–1900	2400–4600	600–700	32–1800	—	40–40 000
Am	10–1000	60–70 000	1600–35000	75–800	—	4–10 000 000

[a] —: Data not available.

TABLE XV-13. RETENTION FACTORS (F_R) OF RU-103, CS-134, CS-137 AND I-131 IN WASHED AND BOILED VEGETABLES COLLECTED IN JAPAN AFTER THE CHERNOBYL ACCIDENT [XV-60]

Type of ratio	Ru-103	Cs-134	Cs-137	I-131
Washed/Raw	0.72	0.65	0.64	0.83
Boiled/Washed	0.72	0.50	0.53	0.51
Boiled/Raw	0.52	0.33	0.34	0.42

XV-6. CONCLUSIONS

Environmental transfer parameters of radionuclides and stable elements obtained in Japan, such as soil-to-crop TF and soil-soil solution distribution coefficients (K_d), have been compiled. We have summarized our experimental results, and also compiled relevant studies carried out in Japan before the Fukushima Daiichi Nuclear Power Plant accident in 2011. The environmental transfer parameters in TRS 364 (1994) collated data mainly from temperate environments. In TRS 472 (2010) some additional data in non-temperate environments were reported. However, the number of transfer parameter data are still limited. Although Japan is in a temperate climate, because it is part of the eastern region of Asia its soil-crop systems differs from that of European and North American countries. Therefore, the data compiled in this study provide relevant parameter values for typical regional characteristics.

The TF values of ^{137}Cs and ^{85}Sr for brown rice were 1.7×10^{-2} and 6.0×10^{-2}. Significant differences in the TF values of ^{137}Cs were observed among the various vegetable species which ranged from 9.0×10^{-3} to 1.4×10^{0}. The TF values of ^{85}Sr had a narrower range (8.1×10^{-1} to 3.7×10^{0}) than those for Cs. The TF values of ^{125}I, Tc, and ^{60}Co for brown rice were less than 5.0×10^{-3}, whereas those of radionuclides related to plant nutrient elements, namely ^{54}Mn and ^{64}Zn, were 2.1×10^{-1} and 3.0×10^{0}, respectively, which were considerably higher than TF values for I, Tc and Co. The TF of stable caesium and strontium for brown rice and polished rice were obtained and compared with those for radiocaesium and radiostrontium. The TF values of stable Cs were 1.3×10^{-3} for brown rice and 7.0×10^{-4} for polished rice and those for stable Sr were 3.8×10^{-3} for brown rice and 1.3×10^{-3} for polished rice. Further comparison of TF values for stable Cs and Sr were carried out with those of global fallout ^{137}Cs and ^{90}Sr. The GMs of TF for global fallout ^{137}Cs were 2.6×10^{-3} for brown rice and 1.1×10^{-3} for polished rice, and the GMs of TFs for ^{90}Sr were 1.5×10^{-2} for brown rice and 5.9×10^{-3} for polished rice. The values for radio and stable forms were similar, although the TFs of ^{137}Cs and ^{90}Sr were usually higher than those of stable Cs and Sr. Global fallout ^{137}Cs and ^{90}Sr in the soil were more bioavailable to plants than stable Cs and Sr for some years after deposition. However, after a long time period, ^{137}Cs and stable Cs and ^{90}Sr and stable Sr have reached an approximate isotopic equilibrium in the bioavailable fraction in the soils. Therefore, the TF of stable Cs and Sr can be used for long-term transfer of ^{137}Cs (and ^{135}Cs) and ^{90}Sr in the environment [XV-26].

The GM of the TFs of stable iodine for fruit vegetables and leafy vegetables were the highest amongst the crops studied. Both TF values were 1.4×10^{-2}, while the lowest value of 3.9×10^{-3} was obtained for brown rice.

The GMs of K_d values for Japanese agricultural soils were: 6.9×10^{2} L/kg for Ni; 8.5×10^{1} L/kg for Se; 2.8×10^{2} L/kg for Sr; 7.2×10^{3} L/kg for Sn; 6.6×10^{1} L/kg for Sb; and 3.2×10^{3} L/kg for Cs. The variations of K_d values were up to two or three orders of magnitude for these radionuclides. The K_d values for Se, Sr, and Cs differed significantly between paddy and upland soil samples by *t*-test ($p < 0.05$), but Sn and Sb did not.

Values for food processing were also collated; the removal percentage of ^{131}I from vegetables contaminated with the Chernobyl fallout was about 10% by gentle washing, and 60-80% by boiling. We also collated data obtained after the Fukushima Daiichi nuclear accident. Decontamination of radiocaesium by food processing for paddy rice, root crops (turnip and radish), fruits (persimmon, apple and loquat) and nuts (chestnut and peanut) were collected by measuring ^{134}Cs and ^{137}Cs. The Cs removal rate by polishing to polished rice was 57-80% with 65% on average. When polished rice was washed, the Cs removal rate was 45%.

After the Fukushima Daiichi nuclear accident, many environmental transfer parameter data were obtained for radiocaesium (^{134}Cs and ^{137}Cs); these data would be able to enhance national and international data sets in the near future [XV-61].

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ANNEX XVI.

SOIL-TO-PLANT TRANSFER FACTORS FOR ^{137}CS IN TROPICAL AREAS IN BRAZIL

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XVI-1. OBJECTIVES

This study focused on the experimental determination of soil-to-plant TF of ^{137}Cs in tropical environments for soybeans, beans, radish, carrot and manioc, using lysimeters. Furthermore, desorption distribution coefficients (K_d) as well as the main geochemical characteristics were determined to facilitate the understanding of the behavior of ^{137}Cs in tropical soils.

XVI-2. MATERIAL AND METHODS

The TF, defined as the ratio between radionuclide activity in the edible part of the crop (Bq/kg DM) and radionuclide activity in the soil (Bq/kg DM), were determined according to the International Union of Radioecology protocols [XVI-1]. The TF were determined for soybeans (*Glycine max*), beans (*Phaseolus vulgaris, L.*), carrot (*Daucus carota, L.*), radish (*Raphanus sativus, L.*) and cassava (*Manihot utilissima*). The plants were cultivated in masonry lysimeters following common agricultural recommendations.

The lysimeters had a surface area of 1 m^2 and were 1 m deep. They were installed in a plot of 10.4 m × 2.7 m, built in a restricted area of the Institute for Radioprotection and Dosimetry (IRD/CNEN, Brazil). The lysimeters were filled with 15 cm of coarse material (sand and gravel), 30 cm of uncontaminated soil and 40 cm of contaminated soil. Three types of soils were used in the experiments. Xantic Ferralsol and Nitisol were artificially contaminated by adding 40 ml of a solution containing ~ 2000 MBq of ^{137}Cs per litre of water for every 2 cm layer. The other soil type is an urban one collected in Goiânia, at a site where a radiological accident occurred in 1987 [XVI-2].

After drying the soil and crop samples, direct measurements of the activity of ^{137}Cs were performed by gamma spectrometry using a NaI detector. Soil analysis was performed by the Brazilian Enterprise for Agricultural Research (EMBRAPA) to characterize the soils and to determine soil needs for fertilization and possible corrections of the nutrient status. The desorption distribution coefficients of ^{137}Cs were determined by batch experiments using 20 g of soil in 70 ml of de-ionized water for 72 hours in two consecutive leaching. The results were expressed as percentage of total ^{137}Cs. Sequential extractions were performed on Goiânia and Ferralsol soils. The method is described in Ref. [XVI-3] and defines five geochemical phases in the following order: exchangeable, carbonate, reducible, oxidizable and residual. Each of the extracts were analyzed by gamma spectrometry using a Ge detector for the determination of ^{137}Cs and by atomic emission spectrophotometry for potassium contents.

XVI-3. RESULTS

XVI-3.1. Description of soils

The results of the pedological analyses are presented in Table XVI-1.

TABLE XVI-1. PEDOLOGICAL ANALYSIS OF SOILS USED

Parameter	Value		
	Ferralsol	Goiânia soil	Nitisol
pH (H_2O)	4.8	7.8	4.9
pH (KCl)	4.3	7.7	4.2
Sand (%)	70	64	10
Clay (%)	24	20	41
Silt (%)	6	16	49
CEC	5.0	10.7	8.4
C (%)	1.15	1.32	1.24
N (%)	0.07	0.09	0.13
P (ppm)	1	50	8
K (meq/100g)	0.09	0.17	0.75
SiO_2 (%)	3.7	7.7	15.7
Al_2O_3 (%)	10.9	13.9	10.2
Ki	0.58	0.94	2.62
Fe_2O_3 (%)	3.9	5.3	13.3
$CaCO_3$ (%)	— [a]	0.92	—
Ca (meq/100g)	—	9.9	—
Na (meq/100g)	0.10	0.17	0.05
Mg (meq/100g)	0.50	0.54	2
Al^{+++} (meq/100g)	0.50	0.0	0.10
H^+ (meq/100g)	3.8	0.1	5.5

[a] —: data not available

Ferralsol – The Ferralsol is an acid soil with an average texture (sandy clay loam), low cation exchange capacity (CEC), low content of clay minerals and nutrient elements. The levels of organic matter and CEC measured are typical of tropical soils, and the value of Ki (a measure for the Al-Fe ratio) is common for soils that are rich in Fe and Al oxides compared to other clay minerals. The mineralogical analysis indicates the presence of gibbsite and kaolinite as the main constituents of the clay mineral fraction. The ensemble of these characteristics is very common in Brazilian soils. This soil was fertilized with urea, potassium chloride and calcium phosphate, to supply the nutritional needs for the crops, which caused the pH to increase to about 6 and made the soil become slightly acid instead of strongly acid.

Goiânia soil – Although the Goiânia soil has also an average texture (sandy clay loam), it is a basic soil, better supplied by nutrient elements; therefore, no fertilization was applied to these soils. The values of Ki were typical of soils that are rich in Fe an Al oxides (compared to other clay minerals). The mineralogical analysis of the clay fraction indicated the presence of gibbsite, kaolinite and interstratified clay illite-smectite.

Nitisol – The Nitisol is an acid silty clay loam soil, with low nutrient content and a low CEC. Values of Ki indicated the predominance of 2:1 clay types, compared with other secondary minerals. The mineralogical analysis indicated the presence of haematite, goetite and traces of vermiculite. It was fertilized with urea, potassium chloride and calcium phosphate.

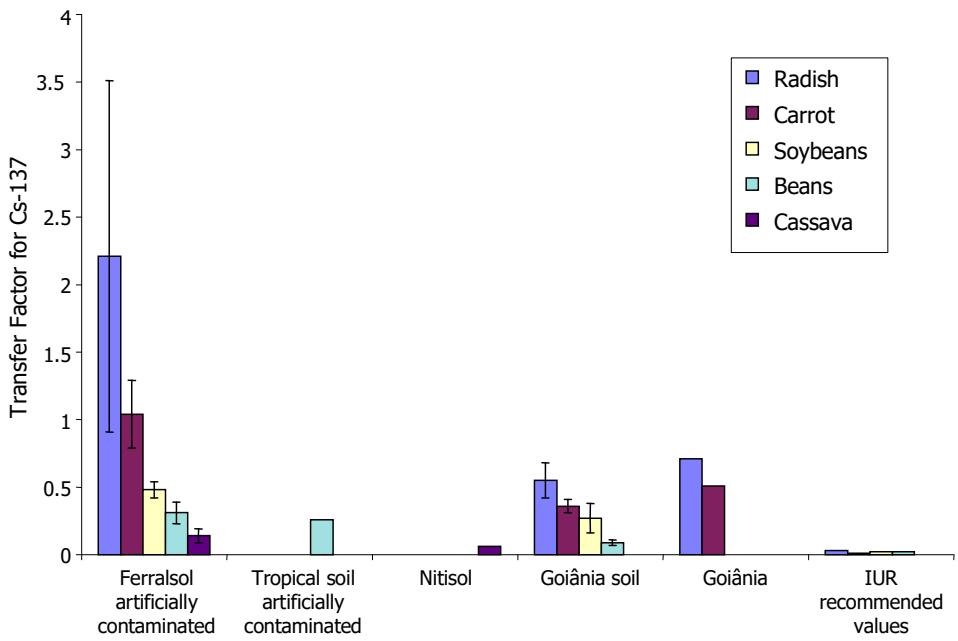

FIG. XVI-1. Soil-to-plant TF of ^{137}Cs obtained in tropical areas [XVI-4, XVI-5] compared with recommended values for temperate environments from Ref. [XVI-1].

XVI-3.2. Transfer factors

Figure XVI-1 presents mean values of TF of ^{137}Cs obtained in the three tropical soils for several crops, compared with some recommended values taken from reference [XVI-1]. The mean values of the soil-to-plant TF of ^{137}Cs obtained for several crops included in the study are higher than the recommended values for temperate environments [XVI-1].

The mean TF of ^{137}Cs for Ferralsol ranged from 0.18 to 0.41 for beans, 0.85 to 1.49 for carrots, 0.89 to 3.5 for radish, 0.41 to 0.56 for soybeans and 0.07 to 0.17 for cassava. Lower TF were obtained for the Goiânia soil: 0.06 to 0.11 for beans, 0.33 to 0.40 for carrots, 0.46 to 0.65 for radish and 0.17 to 0.38 for soybeans (see Fig. XVI-1).

Only one transfer factor of ^{137}Cs for cassava in the acid Nitisol was determined. Its value was very close to that obtained with Ferralsol (0.06). For the same crop, TF obtained using Goiânia soil are slightly lower than those obtained with Ferralsols. The mean transfer factor of ^{137}Cs for beans obtained with Ferralsol agree with the value for an artificially contaminated tropical soil reported in the literature [XVI-4]. In the same way our data for radish and carrot agree with data obtained for the same crops cultivated in a greenhouse using soil from Goiânia [XVI-4].

As can be seen in Figure XVI-1, TF of ^{137}Cs tend to vary significantly between species; the highest values were found for radish, followed in decreasing order by those for carrot, soybeans, beans and cassava.

Figures XVI-2 and XVI-3 show mean ^{137}Cs TF and biomass determined for different parts of soybeans during the growing period. The figures show that all parts of the soybeans have a similar behavior; the TF peak occurring during the first growing phase and then decreasing with time, while the biomass increases with time.

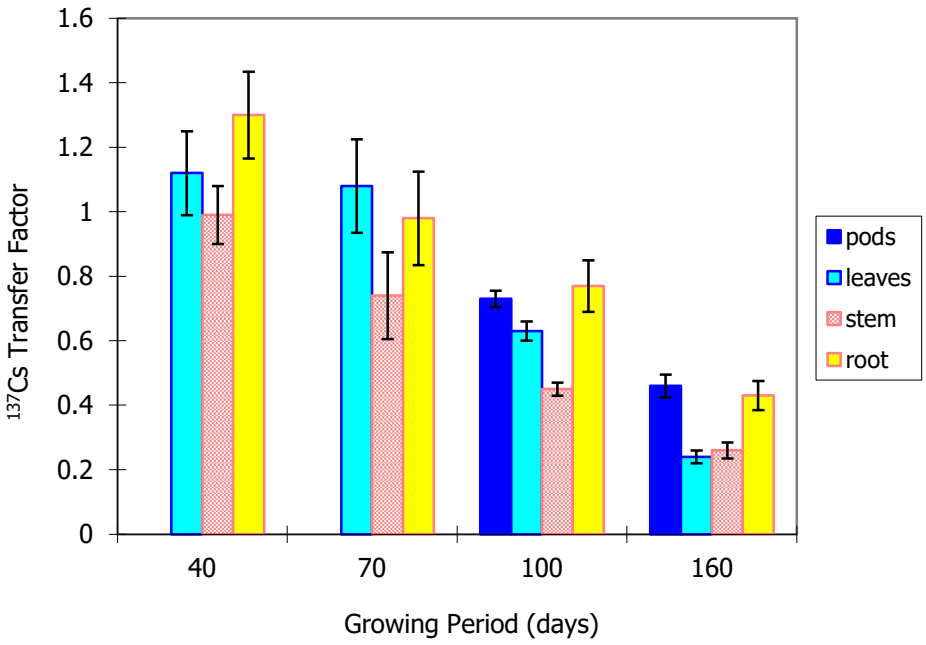

FIG. XVI-2. TF of ^{137}Cs in soybean parts during the growing period (n=4).

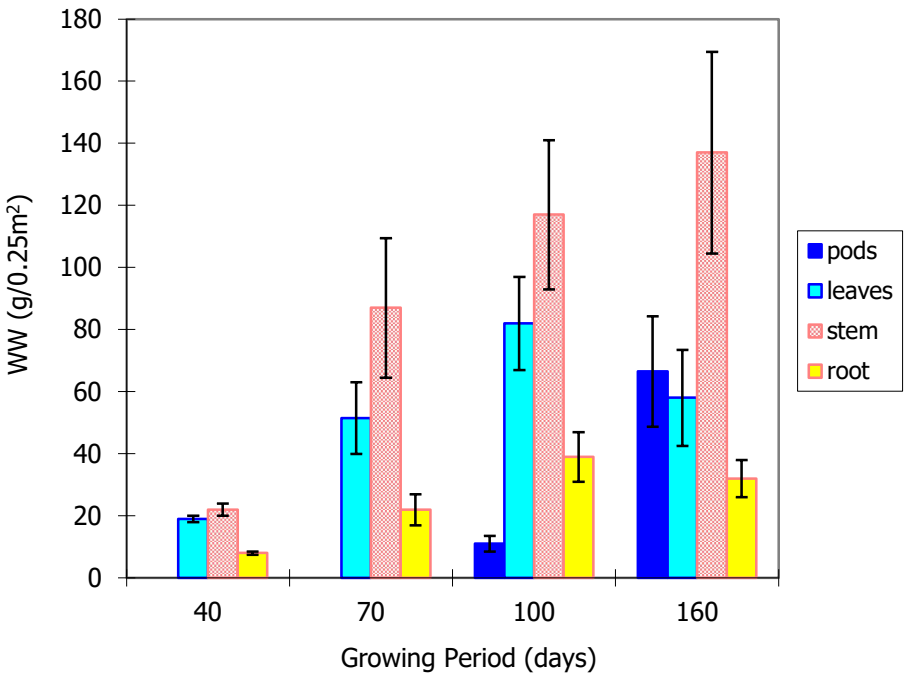

FIG. XVI-3. Dry matter production in soybeans parts during the growing period (n=4).

TABLE XVI-2 PERCENTAGE OF CS-137 DESORBED BY WATER

Lysimeter	First leaching	Second leaching
L1 Ferralsol	0.26	0.21
L2 Ferralsol	0.13	0.11
L3 Ferralsol	0.22	0.17
L4 Ferralsol	0.05	ND
L5 Ferralsol	0.22	0.17
L6 Ferralsol	0.14	ND
L9 Goiânia soil	ND	0.18
L10 Goiânia soil	ND	0.16

XVI-3.3. Desorption results

Percentages of ^{137}Cs desorbed from soil by two consecutive leaching are shown in Table XVI-2. These results show that a higher percentage of ^{137}Cs is leached from Ferralsol than from the Goiânia soil, confirming differences between these soils.

XVI-3.4. Results of the sequential extraction

The results of the geochemical partitioning of ^{137}Cs and potassium of the tropical soils are presented in Fig. XVI-4. About 20% of potassium was observed in the exchangeable phase in both soils. Nevertheless, only very little ^{137}Cs was detected in this phase (<10%) in Ferralsol, while for the Goiânia soil no exchangeable ^{137}Cs was detectable. The concentrations of ^{137}Cs and K associated to the carbonate phase are assumed to refer to the soluble fraction under slightly acid pH conditions (pH ~ 5). About 20% of total potassium, in both soils, became soluble under the slightly acid conditions. About 28% of the total ^{137}Cs became available in Ferralsol under the slightly acid conditions, compared with 17% in the Goiânia soil. The potassium and ^{137}Cs in both soils showed low affinity to organic compounds (<5% and about 17% respectively), as is shown by the low amounts which were released after oxidation. (see Fig. XVI-4). In both soils, ^{137}Cs and K showed higher affinity for Fe-oxides (reducible phase, see Fig. XVI-4). Considering the Goiânia soil, 60% of the total ^{137}Cs was preferentially associated to Fe-oxide structures, while in Ferralsol only 40% of the total ^{137}Cs was associated with this phase. Despite the long period since the contamination in both soils, ^{137}Cs was not detectable in the residual phase, which proves that it remains potentially available for root uptake. Results for potassium showed that about 25% of this element is associated with the mineral structures.

XVI-4. DISCUSSION

XVI-4.1. Geochemical distribution

Elements originating from human activities are associated with different physico-chemical phases in soils, according to their chemical form and characteristics. The geochemical distribution of a radionuclide provides an indication of its potential bioavailability. Elements present in the residual phase are generally considered to be strongly fixed within the lattice structure of primary and secondary minerals and have a low bioavailability [XVI-3].

Low soil-to-plant ^{137}Cs TF reported for temperate climates are due to the strong association of caesium to soil constituents. Radiocaesium that is located in the residual phase becomes less bioavailable with time, as it is progressively fixed within clay structures (2:1 clay types) generally within a few years after deposition [XVI-6, XVI-7].

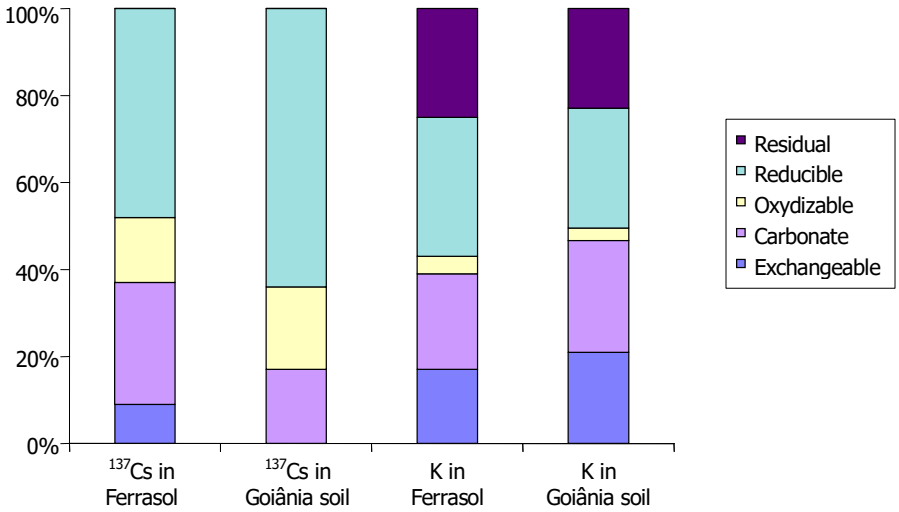

FIG. XVI-4. Geochemical partitioning of ^{137}Cs and K in Ferralsol and Goiânia soil.

Based on sequential extraction results, ^{137}Cs added to the tropical soils used in the experiment remains potentially available for root uptake, since no ^{137}Cs was found in the residual phase, despite the long period of contamination in both soils. Cs-137 was added to the Ferralsol three years before sampling and analysis and the accidental contamination in Goiânia soil had occurred eight years before sampling and analysis. In both of these soils, the predominant clays are of the 1:1 type, represented by kaolinites, which shows a lower cation fixation capacity, due to its molecular structure and low cation exchange capacity, than that of 2:1 clays. The data presented in Fig. XVI-1, show higher TF for ^{137}Cs than those recommended for temperate environment [XVI-1].

The main geochemical phases controlling ^{137}Cs availability in tropical soils seem to be the Fe-oxides, instead of clay minerals as in soils from temperate climates. Since Fe and Al oxides can act as cement between clay minerals and organic matter to form soil aggregates [XVI-8], reducing conditions, such as those simulated by the sequential extraction, may reduce Fe (III) and alter the stability of these aggregates, releasing the elements sorbed on these clays and organic matter. Probably, part of the radionuclides present at the exchange sites, tend to be maintained in these aggregates in tropical soils, thus reducing root uptake with time: 8 years after the Goiânia accident 60% of ^{137}Cs was associated to the Fe-oxide structures while no ^{137}Cs in the exchangeable phase was found, against 40% in the reducible phase and about 10% in the exchangeable phase observed in Ferralsol. Lima [XVI-9] had already noticed the importance of this fraction for ^{226}Ra distribution in Oxysols; a higher radioactive caesium transfer to plants is expected in these soils.

The dystrophic characteristics of tropical soils seem to increase ^{137}Cs root uptake. The TF of ^{137}Cs obtained with the Goiânia soil were slightly lower than those obtained with Ferralsol. Results of the desorption study confirm the differences in availability of ^{137}Cs between soils. The main pedological differences between Ferralsol and Goiânia soil refer to nutrient status and pH. These results suggest that basic soils, better supplied by nutrient elements, reduce ^{137}Cs TF. Although Nitisol contains a 2:1 clay type, its contamination occurred recently (1996), so little time was available for the immobilization of ^{137}Cs in its clay structure. The TF of ^{137}Cs obtained with Nitisol were very close to those obtained with Ferralsol. These soils are very similar in

relation to pH and nutrients levels, confirming again the influence of these parameters on ^{137}Cs root uptake.

XVI-4.2. Desorption

A number of studies have demonstrated that the addition of potassium (and to a lesser extent, ammonium) can desorb caesium from soil owing to competition for specific exchange sites, thus increasing the availability of ^{137}Cs [XVI-10–XVI-13]. The results of studies carried out with some tropical soils show that since availability of ^{137}Cs is not controlled by clay minerals, potassium competition for specific exchange sites does not explain the uptake of this radionuclide.

XVI-4.3. Role of the carrier

The most acceptable hypothesis for the uptake mechanism is the one that stresses the role of a carrier, which facilitates uptake. Due to the chemical similarity between ^{137}Cs and potassium, the carrier does not discriminate between them and therefore ^{137}Cs is well taken up by plants. Therefore, soils containing low concentrations of potassium should favor caesium root uptake, due to competition for carriers. The TF of ^{137}Cs determined for different parts of soy beans during the growing period indicated a considerable mobility of this radionuclide in the plant, since all parts tend to show the same behavior: a peak of concentration during the first growing phase followed by a decrease with time. The behavior of the soybean biomass of all crop parts, suggests that the concentration of ^{137}Cs may undergo a relative dilution due to the increase in biomass. Therefore, a better nutrient supply for crops, besides favoring competition with potassium for carriers, promotes a relative dilution of ^{137}Cs by increasing biomass.

XVI-4.4. Role of pH

The pH of the soil can affect the availability of the elements present in the soil in different ways [XVI-14]. Availability of some nutrients increases when pH values are higher than 6.5, but under high pH conditions, insoluble precipitates of phosphates, carbonates or sulphates can be formed, considerably decreasing the availability of other elements to plants. Slightly acid conditions, as simulated by the sequential procedure in the carbonate phase (pH = 5), showed that ^{137}Cs is displaced towards the solution or that some precipitates of Ferralsol are dissolved. This behavior is not observed in the Goiânia soil. It is important to note that the Ferralsol is an acid soil and by determining the exchangeable phase, the pH increases from 4.8 to 7, possibly retaining some exchangeable ^{137}Cs, which is released in the carbonate phase. Mello et al. [XVI-15] observed that potassium strongly bound to soil compounds becomes exchangeable when acid conditions prevailed. Therefore, results for the carbonate phase must be carefully interpreted, since sorption mechanisms due to the increase of the pH can affect the exchangeable ^{137}Cs.

XVI-4.5. Tissue

Caesium in the tropical soils included in our study showed low affinity to organic compounds (oxidizable phase). In living tissues, potassium is mostly found dissolved in the cell sap in an ionic form and no organic compound has been identified in which potassium constitutes an essential element. This explains the rapid release of this element at the early stages of decomposition of plants [XVI-16, XVI-17]. Since the abundance of ^{137}Cs in a plant has shown to be related to potassium in soil, low potassium contents cause higher TF to plants and consequently, a higher proportion of ^{137}Cs associated to this phase compared to potassium, as we observed in Ferralsol.

XVI-5. CONCLUSION

Sequential extraction of a typical tropical soil showed that all of the ^{137}Cs added to the soil was potentially bioavailable for root uptake. Some tropical soil characteristics such as acidity, low availability of nutrient elements and low content of 2:1 clay type were associated with higher transfer factor of ^{137}Cs from soil to plants, when compared with TF from temperate climates.

Some pedological differences between different climatic conditions, indicate the need to improve the generation of regional TF to be able to make accurate dose assessments.

XVI-6. ACKNOWLEDGMENTS

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