TECHNICAL REPORTS SERIES NO. 422

Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment

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SEDIMENT DISTRIBUTION COEFFICIENTS AND CONCENTRATION FACTORS FOR BIOTA IN THE MARINE ENVIRONMENT

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Printed by the IAEA in Austria
April 2004
STI/DOC/010/422

TECHNICAL REPORTS SERIES No. 422

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2004

IAEA Library Cataloguing in Publication Data

Sediment distribution coefficients and concentration factors for biota in the marine environment. — Vienna, International Atomic Energy Agency, 2004.
p. ; 24 cm. — (Technical reports series, ISSN 0074–1914 ; no. 422)
STI/DOC/010/422
ISBN 92–0–114403–2
Includes bibliographical references.

1. Marine sediments. 2. Aquatic organisms. I. International Atomic Energy Agency. II. Series: Technical reports series (International Atomic Energy Agency) ; 422.

IAEAL 04-00355

FOREWORD

In 1985 the IAEA published Technical Reports Series No. 247 (TRS 247), Sediment K_ds and Concentration Factors for Radionuclides in the Marine Environment, which provided sediment distribution coefficients (K_ds) and concentration factor (CF) data for marine biological material that could be used in models simulating the dispersion of radioactive waste that had been disposed of in the sea. TRS 247 described an approach for calculating sediment or water K_ds using stable element geochemical data developed by J.M. Bewers, even though the use of field derived data was emphasized whenever possible.

Over the years, TRS 247 has proved to be a valuable reference for radioecologists, marine modellers and other scientists involved in assessing the impact of radionuclides in the marine environment. In 2000 the IAEA initiated a revision of TRS 247 to take account of the new sets of data obtained since 1985. The outcome of this work is this report, which contains revised sediment K_ds for the open ocean and ocean margins and CFs for marine biota. CFs for deep ocean ferromanganese nodules, which were provided in Table II of TRS 247, can now be found in the Appendix. In addition, this report contains CFs for a limited number of elements for marine mammals not included in TRS 247.

This revision was carried out at three IAEA Consultants Meetings held in Monaco and Vienna between April 2000 and December 2002. The IAEA wishes to acknowledge the contribution of those responsible for the drafting and review of this report. Their names are listed at the end of this report. The IAEA officers responsible for this project were S.W. Fowler of the Marine Environmental Laboratory, Monaco, and T. Cabianca of the Division of Radiation and Waste Safety, Vienna.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND TO TECHNICAL REPORTS SERIES No. 247

The oceans and coastal waters are influenced by a complex variety of physical, geochemical and biological processes, which influence the behaviour, transport and fate of radionuclides released into the marine environment. Key parameters describing these processes are represented in models that may be used either to assess the impact of radionuclide contributions or to develop regulations for controlling the release of radionuclides into the marine environment.

In the decade prior to the publication of Technical Reports Series No. 247 (TRS 247) [1] there had been considerable international effort to investigate the potential impact of existing low level solid waste disposal [2] and the potential suitability of the sub-seabed disposal of high level waste [3]. This resulted in a number of initiatives, including a GESAMP[1] report, An Oceanographic Model for the Dispersion of Wastes Disposed of in the Deep Sea [4]. It was recognized that the representation of geochemical and biological processes in such models by means of distribution coefficients (K_ds) and concentration factors (CFs) (see Sections 2 and 3 for their definitions) was sometimes inadequate and in any case poorly documented. The original version of TRS 247 described an approach based both on stable element abundances and literature K_ds and CFs, with emphasis on field observations for selection of the latter when available. These recommended values could then be used in models designed to provide the definition of radioactive waste unsuitable for dumping at sea [5], as required by annex I of the then London Dumping Convention.

1.2. CHANGES SINCE THE PUBLICATION OF TRS 247

A number of significant developments have occurred since the publication of TRS 247, including changes to the regional and international regulatory framework controlling radionuclide inputs to the marine environment, changes in the type and extent of radionuclide inputs, greater disclosure of previous

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[1] GESAMP (International Maritime Organization, Food and Agriculture Organization of the United Nations, United Nations Educational, Scientific and Cultural Organization, World Meteorological Organization, World Health Organization, IAEA, United Nations, United Nations Environment Programme Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection).

at-sea waste disposal practices by nations and a number of post-TRS 247 international radiological assessments, in addition to those carried out as part of routine national programmes [6–8].

1.2.1. Regional and international regulatory framework

The most significant changes to the international regulatory framework since 1985 have been:

(a) In 1992 the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) was adopted by the 14 signatory states to the Oslo and Paris Conventions, Switzerland and the European Commission (EC). The OSPAR Convention commits the Contracting Parties to take all possible steps to prevent and eliminate pollution of the marine environment of the northeast Atlantic by applying the precautionary approach and using the best environmental technologies and environmental practices. At the 1998 Ministerial Meeting of the OSPAR Commission held in Sintra the signatories to the OSPAR Convention pledged to undertake a progressive and substantial reduction of discharges, emissions and losses of radioactive substances, with the ultimate aim of reducing concentrations in the environment to near background levels for naturally occurring radioactive substances and close to zero for artificial radioactive substances. In achieving this objective, issues such as legitimate uses of the sea, technical feasibility and radiological impacts on humans and biota should be taken into account [9].

(b) In 1993 the Sixteenth Consultative Meeting of the London Convention 1972 adopted Resolution LC.51(16), amending the London Convention and prohibiting the disposal at sea of all radioactive waste and other radioactive matter [10]. The resolution entered into force on 20 February 1994 for all Contracting Parties, with the exception of the Russian Federation, which had submitted to the Secretary General of the International Maritime Organization (IMO) a declaration of non-acceptance of the amendment contained in Resolution LC.51(16), although stating that it will continue its endeavours to ensure that the sea is not polluted by the dumping of waste and other matter.

(c) In the past few years there has been an increasing emphasis on the need to address radiological impacts on the environment as a whole, including non-human biota. The long held view that protection of the environment was assured as a consequence of protecting the human population, endorsed by International Commission on Radiological Protection

(ICRP) Publication 60 [11], is at present under review. In 1999 the IAEA published a discussion report [12] on the protection of the environment from the effects of ionizing radiation. The European Union has recognized the need for further initiatives [13], and this issue is under discussion in the peer reviewed scientific literature [14–16].

(d) In 1996 the IAEA adopted the new Basic Safety Standards for radiation protection [17]. These International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources were based on the recommendations of the ICRP and were sponsored by five other organizations: the Food and Agriculture Organization of the United Nations, the International Labour Organization, the OECD Nuclear Energy Agency, the Pan American Health Organization and the World Health Organization. Over the past few years the Basic Safety Standards have become the basis for national regulations in a large number of countries and their adoption has led many countries to review and revise their relevant national regulations.

1.2.2. Radionuclide sources

The most significant events since the publication of TRS 247 that have led to an actual or potential input of radionuclides into the marine environment have been the following.

(a) The accident at the Chernobyl nuclear power plant in April 1986 was the single largest contribution to radioactivity in the marine environment resulting from accidental releases from land based nuclear installations. The most radiologically significant radionuclides released in the accident were ^{137}Cs, ^{134}Cs, ^{90}Sr and ^{131}I. The inventories of ^{137}Cs and ^{134}Cs of Chernobyl origin in northern European waters, from direct deposition and runoff, were estimated to be 10 PBq and 5 PBq [18], respectively, affecting mainly the Baltic Sea. It has also been estimated that the total input of ^{137}Cs into the Mediterranean Sea and Black Sea was between 3 and 5 PBq and 2.4 PBq, respectively [19].

(b) In May 1993 the Russian Federation disclosed information on sea disposal operations of the Former Soviet Union (FSU) and the Russian Federation in the Kara Sea, Barents Sea and Sea of Japan [20]. In October of the same year the Russian Federation informed the IAEA and IMO about a liquid waste disposal operation that had taken place in the Sea of Japan in 1993 [21]. Additional information on disposal operations carried out by Sweden in 1959 and 1961 in the Baltic Sea and by the United Kingdom in its coastal waters from 1948 to 1976 was also made public in 1992 and 1997 [22, 23].

In addition, changes in the pattern of routine releases of radioactive waste into the sea have also occurred.

(i) Since the mid-1980s there have been significant changes in the relative composition and quantities of discharges of radioactive material to rivers and coastal waters, especially from nuclear fuel reprocessing installations. Overall discharges to the sea from nuclear installations in mid-latitudes have been reduced in the intervening period. Conversely, changes in waste management practices at the nuclear fuel reprocessing plants at Cap de la Hague (France) and Sellafield (UK) led to increases in discharges of ^{129}I and ^{99}Tc in the 1990s. This has been accompanied by an upsurge in interest in the use of ^{99}Tc and ^{129}I as tracers of oceanographic processes [24, 25]. As a result, there are far more data available on these radionuclides than at the time of the compilation of TRS 247. The high accumulation rates of ^{99}Tc by some biota stimulated a limited number of field measurements, from which additional CFs have been derived.

(ii) Since the early 1990s it has been recognized that contaminated seabed sediments represent significant secondary sources of radionuclides; for example, since the 1980s the Irish Sea seabed has been a more significant source of caesium and plutonium to the water column than direct discharges from Sellafield [25, 26]. The phenomenon is also thought to occur in the Baltic Sea as a result of the deposition that followed the accident at Chernobyl and in the Rhone Delta in the Mediterranean Sea, which was the recipient of radioactive waste from the nuclear fuel reprocessing plant at Marcoule [27].

(iii) In recent years there has also been an increased recognition of the radiological significance of non-nuclear sources of natural radioactivity, in particular ^{226}Ra, ^{228}Ra, ^{222}Rn, ^{210}Pb and ^{210}Po, produced, for example, by phosphate processing plants, offshore oil and gas installations and the ceramics industry [28–31].

1.2.3. Radiological assessments

Since the publication of TRS 247 a number of international assessments have been carried out.

(a) Between 1985 and 1996 the EC commissioned three assessments of the radiological exposure of the population of the European Community from radioactivity in north European marine waters (Project Marina [18]), the Mediterranean Sea (Project Marina-Med [19]) and the Baltic Sea (Project Marina-Balt [32, 33]). In 2000 the European Union initiated a revision of the original Marina project. This study took account of changes in direct discharges from nuclear installations and remobilization from contaminated sediments, used more realistic habit data to derive doses to critical groups and placed more emphasis on the impact of naturally occurring radioactive material from the processing of phosphate ore and from the offshore oil and gas industry [34].

(b) In the early 1990s an IAEA Co-ordinated Research Project, Sources of Radioactivity in the Marine Environment and their Relative Contributions to Overall Dose Assessment from Marine Radioactivity, conducted a global radiological assessment of doses to members of the public from ^{210}Po and ^{137}Cs through the consumption of seafood [35, 36].

(c) Following the disclosure that the FSU had dumped radioactive waste in the shallow waters of the Arctic Seas, in 1993 the IAEA established the International Arctic Seas Assessment Project (IASAP) with the objectives of specifically examining the radiological conditions in the western Kara Sea and Barents Sea and assessing the risks to human health and the environment associated with the radioactive waste disposed of in those seas [37–40]. A detailed review of K_ds and CFs for marine biota was carried out as part of this project. There have been several other related initiatives that have been part of larger international, multilateral or national programmes, such as the Arctic Monitoring and Assessment Programme (AMAP), the Joint Russian–Norwegian Expert Group for the investigation of radioactive contamination in northern areas and the US Arctic Nuclear Waste Assessment Programme (ANWAP).

(d) Between 1996 and 1998 the IAEA conducted an international study to assess the radiological consequences of the 193 nuclear experiments (nuclear tests and safety trials) conducted by the French Government at Mururoa and Fangataufa Atolls in the South Pacific Ocean [41]. A large number of measurements of radionuclide concentrations in sea water, sediments and marine biota were collected during this investigation.

(e) In the same years the IAEA also undertook a review of the assessments of the radiological conditions at Bikini Atoll in relation to nuclear weapon tests carried out in the territory of the Marshall Islands between 1946 and 1958 [42].

(f) The Nord-Cotentin Radioecology Group was set up by the French Government in 1997 to conduct an assessment of the region adjacent to the reprocessing plant at Cap de la Hague in northwest France. This included a consideration of marine pathways and the derivation of K_ds and CFs from field measurements. The work of this group was completed in 1999 [43].

(g) In recent years a number of assessments have been carried out of the radiological consequences resulting from European non-nuclear activities, such as the extraction of phosphogypsum by the phosphate processing industry [44, 45].

1.3. IMPROVED SCIENTIFIC KNOWLEDGE

The developments that followed the publication of TRS 247 have led to a greater concentration of effort on coastal, estuarine and shelf processes and on the behaviour and impact of radionuclides in these environments. Much of the field data in TRS 247 were based on temperate regions and there has been concern expressed as to the applicability of the derived K_ds and CFs to other regions. Since then there has been an increased emphasis on Arctic and, to a lesser extent, tropical environments (Mururoa, Bikini), reflecting changing circumstances and the radiological assessments that have been undertaken subsequently. In some cases assessments have used the K_ds and CFs recommended in TRS 247. However, there have been specific studies to improve the database on radionuclide partitioning in response to particular radiological issues. Increased discharges of ^{99}Tc from the Sellafield reprocessing plant in the mid-1990s created a need to improve the database of ^{99}Tc in crustaceans (see Table IV). The initial IASAP calculations were performed using values taken from TRS 247, but the pressure to conduct a thorough radiological assessment of the Kara Sea dumping operations led to an experimental programme to provide site specific K_ds using sediment collected from the region [46, 47]. The Mururoa and Nord-Cotentin assessments also used site specific CFs.

There have been significant advances in the fields of chemical and biological oceanography since the publication of TRS 247. This applies both to the understanding of oceanographic processes and to the provision of reliable data on element concentrations in sea water [48]. Wherever possible these improvements in our knowledge base have been incorporated into this report.

Many of the sediment K_ds and biological CFs provided in this report differ significantly from the values published in TRS 247. These new values reflect new measurements primarily coming from coastal regions, often as part of national monitoring programmes, such as the National Oceanic and Atmospheric Administration's National Status and Trends Program in the United States of America, that follow standardized sampling and analytical protocols. In addition, in many cases the new CFs reflect the latest understanding of dissolved element concentrations in sea water (provided in Tables I and II); for example, with the increased application of clean sampling and analytical techniques for trace metal determination, a more reliable and internally consistent oceanographic data set now exists for dissolved metal concentrations. Typically the recent metal measurements are significantly below earlier estimates of dissolved concentrations. Consequently, in calculating sediment K_ds or CFs for organisms using wet weight concentrations of metals in organism tissues, the new metal CFs published in this report are generally higher than those in TRS 247. In addition, improved sampling and analytical protocols for measuring the concentrations of radionuclides in sea water, sediments and biological tissues have generated a more reliable database for some radionuclides and their stable analogues, leading to altered recommended sediment K_ds and CFs.

1.4. ENVIRONMENTAL IMPACT

Until relatively recently it was assumed that protection of the environment was assured as a consequence of protecting the human population. This hypothesis was endorsed in ICRP 60 [11]:

> "The Commission believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk."

This assumption is now being challenged on the grounds that there may be situations in which it is not valid and that there is a need to demonstrate that environmental protection has been specifically addressed [15]. The assessments carried out by the IASAP [38] and AMAP in the area where the Russian nuclear submarine Komsomolets sank [49] both included estimations of ecological risk, and in both cases the risk was found to be negligible.

There is now a requirement under annex V of the OSPAR Convention [9] to acknowledge "the protection and conservation of the ecosystems and biological diversity of the maritime area". International symposia have been recently organized around this topic [50, 51]. In 1999 the IAEA issued a report for discussion, in which the need for developing a system for protecting the environment against the effects of ionizing radiation was elaborated [12]. In 2000 and 2001 the IAEA held two specialist meetings on the subject, at which the ethical principles that could underlie such a system were explored [52].

The biological data compiled in this study are likely to be of limited value for predicting radiological effects on biota. The distribution of radionuclides in specific organs will be more critical for assessing harm to the organism, and is a topic beyond the scope of this report. The focus of this report is to provide information that would allow an assessment of the potential risks associated with human consumption of edible fractions.

1.5. USE OF RECOMMENDED K_ds AND CFs IN MODELS

The following sections provide recommended K_ds or CFs for use in radiological assessment models. They can be thought of as best estimates or default values in the absence of site specific data, and replace the mean values of TRS 247. It is recommended that the explanatory footnotes accompanying the tables be consulted, as these may refer the user to more detailed information that may be of relevance to particular assessments. No attempt has been made to provide statistical distributions of K_ds or CFs for each element–matrix combination. There are very few cases where the database is adequate to derive a distribution empirically. It is suggested that the influence of the K_d or CF should be included in a model sensitivity analysis using arbitrary parameter distributions, and that further site specific values be sought if necessary. Ranges of K_ds and CFs have been removed from the revised tables. In most cases maximum and minimum values can be assumed to be within one order of magnitude of the recommended value.

2. SEDIMENT–WATER DISTRIBUTION COEFFICIENTS

2.1. INTRODUCTION

This section provides details of the approach adopted for the derivation of sediment–water K_ds for use in radiological assessment models of the marine environment. The K_d provides a convenient means to describe the relationship between radionuclide concentrations in suspended particulate matter or bottom sediments and water:

$$K_d \text{ (dimensionless)} = \frac{\text{Concentration per unit mass of particulate (kg/kg or Bq/kg dry weight)}}{\text{Concentration per unit mass of water (kg/kg or Bq/kg)}}$$

or:

$$K_d\ (\mathrm{L/kg}) = \frac{\text{Concentration per unit mass of particulate (kg/kg or Bq/kg dry weight)}}{\text{Concentration per unit volume of water (kg/L or Bq/L)}}$$

By adopting the K_d concept we have to assume that there exists an equilibrium balance between dissolved and particulate phases, with the exchanges of nuclides between particles and water being wholly reversible. This is a simplification of reality, especially for short timescale exchanges, but is justifiable for the purposes of running most radiological assessment models, particularly when there is inadequate knowledge about the actual distribution and behaviour of relevant radionuclides. An important exception is in cases where the presence of hot particles [53, 54] must be taken into consideration in the radiological risk assessment. It does not preclude the use of more realistic modelling techniques when the needs of the assessment and the availability of data justify it. Usually it is not known whether the K_d represents equilibrium partitioning between water and all the particulate phases that are available for exchange over varying times and whether the partitioning involves wholly reversible or some irreversible processes.

K_ds have been determined from both field observations and laboratory sorption experiments for several radionuclides of radiological significance. Such data are essential for artificial nuclides; however, for nuclides of naturally occurring elements it is possible to use an alternative approach to the derivation of K_ds based on the use of stable element geochemical data and the choice of reasonable, if arbitrary, assumptions. In this way we can assess the proportions of the particulate phase abundances of the elements that are likely to be exchangeable with the aqueous phase. Combining both approaches provides a best estimate value for each element that can be used as a generic value.

2.2. OPEN OCEAN K_ds (TABLE I)

2.2.1. Derivation of open ocean K_ds

Recommended K_ds for the open ocean environment for a number of elements are listed in column 2 of Table I. In addition, a selection of K_ds based on field observations or laboratory experiments has been compiled and is presented in the last column, where possible using values published in peer reviewed literature. The remainder of Table I contains the details from which the recommended values were calculated.

TABLE I. OPEN OCEAN K_ds

Element	Recommended K_d value[a]	Deep pelagic seawater concentration (kg/kg)	Total pelagic clay[a] (kg/kg) [55]	Pelagic carbonate concentration (kg/kg) [55]	Mean shale concentration[a] (kg/kg) [55]
H	1×10^{0}	1.1×10^{-1} [1]	—	—	—
C	2×10^{3}	5.0×10^{-7} [1]	4.5×10^{-3}	—	—
	—	2.8×10^{-5} [1]	4.5×10^{-3}	6.6×10^{-2}	1.4×10^{-2}
Na	1×10^{0}	1.1×10^{-2} [1]	1.1×10^{-2}	5.9×10^{-3}	5.9×10^{-3}
S	1×10^{0}	9.0×10^{-4} [1]	1.3×10^{-3}	1.3×10^{-3}	2.4×10^{-3}
Cl	1×10^{0}	1.9×10^{-2} [1]	2.2×10^{-2}	2.1×10^{-2}	1.6×10^{-4}
Ca	5×10^{2}	4.1×10^{-4} [1]	1.0×10^{-2}	2.0×10^{-1}	1.6×10^{-2}
Sc	7×10^{6}	8.6×10^{-13} [48]	1.9×10^{-5}	2.0×10^{-6}	1.3×10^{-5}
Cr	4×10^{5}	2.5×10^{-10} [48]	9.0×10^{-5}	1.1×10^{-5}	9.0×10^{-5}
Mn	2×10^{8}	2.7×10^{-11} [48]	6.7×10^{-3}	1.0×10^{-3}	8.5×10^{-4}
Fe	2×10^{8}	4.4×10^{-11} [48]	5.8×10^{-2}	2.7×10^{-2}	4.8×10^{-2}
Co	5×10^{7}	1.2×10^{-12} [48]	7.4×10^{-5}	7.0×10^{-6}	1.9×10^{-5}
Ni	3×10^{5}	5.2×10^{-10} [48]	2.3×10^{-4}	3.0×10^{-5}	6.8×10^{-5}
Zn	2×10^{5}	3.2×10^{-10} [48]	1.7×10^{-4}	3.5×10^{-5}	1.2×10^{-4}
Se	1×10^{3}	1.5×10^{-10} [48]	1.7×10^{-7}	1.7×10^{-7}	5.0×10^{-7}
Kr	1×10^{0}	2.0×10^{-10} [1, 60]	—	—	—
Sr	2×10^{2}	8.8×10^{-6} [60]	1.8×10^{-5}	2.0×10^{-3}	3.0×10^{-4}
Y	7×10^{6}	4.5×10^{-12} [60]	3.2×10^{-5}	4.2×10^{-5}	4.1×10^{-5}
Zr	7×10^{6}	2.0×10^{-11} [48]	1.5×10^{-4}	2.0×10^{-5}	1.6×10^{-4}
Nb	3×10^{5}	4.7×10^{-12} [60]	1.4×10^{-5}	4.6×10^{-6}	1.8×10^{-5}
Tc	1×10^{2}	—	—	—	—
Ru	(1×10^{3})	5.1×10^{-15} [60]	(1.0×10^{-9})	—	—
Pd	5×10^{3}	7.0×10^{-14} [48]	3.7×10^{-9}	7.0×10^{-9}	—
Ag	2×10^{4}	2.5×10^{-12} [48]	1.1×10^{-7}	6.0×10^{-8}	7.0×10^{-8}
Cd	3×10^{3}	7.6×10^{-11} [48]	2.1×10^{-7}	2.3×10^{-7}	2.2×10^{-7}
In	1×10^{5}	1.0×10^{-13} [48]	7.0×10^{-8}	2.0×10^{-8}	5.7×10^{-8}
Sn	3×10^{5}	9.5×10^{-13} [48]	3.2×10^{-6}	1.5×10^{-6}	6.0×10^{-6}
Sb	4×10^{3}	2.4×10^{-10} [1, 60]	1.0×10^{-6}	1.5×10^{-7}	1.5×10^{-6}
Te	(1×10^{3})	1.1×10^{-13} [48]	—	—	—
I	2×10^{2}	6.4×10^{-8} [1, 60]	3.0×10^{-5}	3.1×10^{-5}	1.9×10^{-5}
Xe	1×10^{0}	4.7×10^{-11} [1, 60]	—	—	—
Cs	2×10^{3}	3.1×10^{-10} [1, 60]	6.0×10^{-6}	4.0×10^{-7}	5.5×10^{-6}
Ba	9×10^{3}	2.1×10^{-8} [68]	2.3×10^{-3}	1.9×10^{-4}	5.5×10^{-4}
Ce	7×10^{7}	3.7×10^{-12} [48]	3.5×10^{-4}	3.5×10^{-5}	9.6×10^{-5}
Pm	(1×10^{6})	—	—	—	—
Pr	8×10^{6}	1.3×10^{-12} [48]	9.6×10^{-6}	3.3×10^{-6}	1.1×10^{-5}

Potential clay enrichment (kg/kg)	K_d based on total pelagic clay (kg/kg)	K_d based on potential enrichment (kg/kg)	K_d based on potential carbonate exchange (kg/kg)	Other derived K_ds
—	—	—	—	—
—	9.0×10^3	—	—	—
—	1.6×10^2	—	2.4×10^3	—
5.1×10^{-3}	1.0×10^0	4.6×10^{-1}	—	1×10^{-1}–2.4×10^0 [56, 57]
—	1.4×10^0	—	—	—
2.2×10^{-2}	1.2×10^0	1.1×10^0	—	—
—	2.4×10^1	—	4.9×10^2	1×10^2 [56]
6.0×10^{-6}	2.2×10^7	7.0×10^6	—	4×10^7–5×10^7 [56, 58]
—	3.6×10^5	—	—	3×10^5–5×10^5 [56, 58]
5.9×10^{-3}	2.5×10^8	2.2×10^8	—	8×10^6–2×10^7 [4, 57, 58]
1.0×10^{-2}	1.3×10^9	2.3×10^8	—	5×10^5–5×10^7 [4, 57, 58]
5.5×10^{-5}	6.2×10^7	4.6×10^7	—	1×10^6–6×10^6 [4, 57, 58]
1.6×10^{-4}	4.5×10^5	3.1×10^5	—	3×10^5–5×10^5 [56, 58]
5.0×10^{-5}	5.3×10^5	1.6×10^5	—	1×10^5–4×10^5 [56–58]
—	1.1×10^3	—	—	8×10^2–1×10^4 [57–59]
—	—	—	—	—
—	2.0×10^0	—	2.5×10^2	1×10^{-1} [56]
—	7.1×10^6	—	—	8×10^7 [56]
—	7.4×10^6	—	—	8×10^6 [56]
—	3.0×10^6	—	—	—
—	—	—	—	1×10^0–1×10^1 [61–66]
—	(2.0×10^5)	—	—	—
—	5.3×10^4	—	—	—
4.0×10^{-8}	4.4×10^4	1.6×10^4	—	3×10^3–5×10^3 [56, 58]
—	2.8×10^3	—	—	9.5×10^1–1×10^4 [56–58]
1.3×10^{-8}	6.7×10^5	1.3×10^5	—	1×10^6 [56]
—	3.4×10^6	—	—	1×10^5 [57]
—	4.1×10^3	—	—	5×10^3–2.1×10^4 [57, 58]
—	—	—	—	—
1.1×10^{-5}	4.7×10^2	1.7×10^2	—	1×10^2–1.3×10^4 [59, 67]
—	—	—	—	—
5.0×10^{-7}	2.0×10^4	1.6×10^3	—	4×10^2–2×10^4 [56–58]
1.8×10^{-3}	1.1×10^5	8.3×10^4	9.0×10^3	2×10^4–1×10^5 [56, 57]
2.5×10^{-4}	9.4×10^7	6.8×10^7	—	1×10^8 [56]
—	(1.0×10^7)	—	—	—
—	7.6×10^6	—	—	2×10^7 [56]

TABLE I. (cont.)

Element	Recommended K_d value[a]	Deep pelagic seawater concentration (kg/kg)	Total pelagic clay[a] (kg/kg) [55]	Pelagic carbonate concentration (kg/kg) [55]	Mean shale concentration[a] (kg/kg) [55]
Sm	5×10^5	1.2×10^{-12} [48]	6.2×10^{-6}	3.8×10^{-6}	7.0×10^{-6}
Eu	2×10^6	3.0×10^{-13} [48]	1.8×10^{-6}	6.0×10^{-7}	1.2×10^{-6}
Gd	7×10^5	2.0×10^{-12} [48]	7.4×10^{-6}	3.8×10^{-6}	6.0×10^{-6}
Tb	4×10^5	2.7×10^{-13} [48]	1.1×10^{-6}	6.0×10^{-7}	1.0×10^{-6}
Dy	(5×10^6)	9.1×10^{-13} [48]	(6.0×10^{-6})	2.7×10^{-6}	5.8×10^{-6}
Tm	2×10^5	2.9×10^{-13} [48]	5.6×10^{-7}	1.0×10^{-7}	6.0×10^{-7}
Yb	2×10^5	1.9×10^{-12} [48]	2.9×10^{-6}	1.5×10^{-6}	3.9×10^{-6}
Hf	6×10^6	2.1×10^{-13} [48]	4.1×10^{-6}	4.1×10^{-7}	2.8×10^{-6}
Ta	5×10^4	2.4×10^{-12} [48]	1.2×10^{-6}	1.0×10^{-8}	2.0×10^{-6}
W	1×10^3	1.0×10^{-10} [1, 60]	1.1×10^{-6}	1.1×10^{-7}	1.9×10^{-6}
Ir	(3×10^6)	1.7×10^{-15} [48]	3.0×10^{-10}	—	(3.0×10^{-12})
Hg	3×10^4	2.5×10^{-13} [60]	8.0×10^{-8}	4.6×10^{-7}	1.8×10^{-7}
Tl	9×10^4	1.0×10^{-11} [1, 60]	9.0×10^{-7}	1.6×10^{-7}	1.2×10^{-6}
Pb	1×10^7	4.0×10^{-12} [1, 60]	8.0×10^{-5}	1.7×10^{-5}	2.3×10^{-5}
Po	(2×10^7)	2.3×10^{-18} [60]	—	—	—
Ra	4×10^3	5.6×10^{-16} [69, 70]	2.0×10^{-11}	2.0×10^{-12}	1.1×10^{-12}
Ac	(2×10^6)	6.9×10^{-20} [60]	—	—	—
Th	5×10^6	1.0×10^{-13} [1, 72]	5.0×10^{-6}	1.0×10^{-6}	1.2×10^{-5}
Pa	(5×10^6)	1.7×10^{-17} [76]	—	—	—
U	5×10^2	3.2×10^{-9} [1, 60]	1.0×10^{-6}	1.6×10^{-6}	3.7×10^{-6}
Np	1×10^3	—	—	—	—
Pu	1×10^5	—	—	—	—
Am	2×10^6	—	—	—	—
Cm	2×10^6	—	—	—	—
Bk	(2×10^6)	—	—	—	—
Cf	(2×10^6)	—	—	—	—

[a] Values in parentheses indicate that data are insufficient to calculate K_ds using the methodology described in Section 2.2.1 and therefore the recommended values were chosen to be equal to the K_ds of periodically adjacent elements.

Potential clay enrichment (kg/kg)	K_d based on total pelagic clay (kg/kg)	K_d based on potential enrichment (kg/kg)	K_d based on potential carbonate exchange (kg/kg)	Other derived K_ds
—	5.1×10^6	—	—	—
6.0×10^{-7}	5.9×10^6	2.0×10^6	—	—
1.4×10^{-6}	3.8×10^6	7.1×10^5	—	—
1.0×10^{-7}	4.0×10^6	3.6×10^5	—	—
2.0×10^{-7}	(6.6×10^6)	(2.2×10^5)	—	—
—	1.9×10^6	—	—	—
—	1.5×10^6	—	—	—
1.3×10^{-6}	2.0×10^7	6.3×10^6	—	1×10^6 [56]
—	5.1×10^5	—	—	—
—	1.1×10^4	—	—	—
—	(1.8×10^5)	—	—	—
—	3.2×10^5	—	—	3×10^3–5×10^3 [56, 58]
—	9.0×10^4	—	—	1×10^5 [56]
5.7×10^{-5}	2.0×10^7	1.4×10^7	—	1×10^4–5×10^7 [4, 56, 59]
—	—	—	—	—
1.9×10^{-11}	3.6×10^4	3.4×10^4	3.6×10^3	5×10^2 [59]
—	—	—	—	—
—	4.9×10^7	—	—	1×10^5–1×10^7 [4, 56, 58, 59, 71, 73–75]
—	—	—	—	1×10^4–1×10^7 [4, 59]
—	3.1×10^2	—	5.0×10^2	5×10^2 [56, 58, 59]
—	—	—	—	1×10^2–5×10^4 (see Section 2.2.2)
—	—	—	—	1×10^4–1×10^6 (see Section 2.2.2)
—	—	—	—	1×10^5–2×10^7 (see Section 2.2.2)
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—

The recommended K_ds (column 2) are based on the estimate of pelagic clay enrichment in relation to source rocks. Where no such enrichment is indicated, it has been assumed, arbitrarily, that 10% of the total pelagic clay abundance represents the proportion of exchangeable phase particulate element. The only exceptions to this procedure are where the experimental measurements, presented in the table, suggest that the K_d is closer to the value based on the total pelagic clay concentration than to the value based on 10% of this concentration (Sc, Cr, Se, Y, Zr, Cd, Sb, Pr and Tl).

Deep water dissolved element concentrations (column 3) represent, in most instances, the mean of Atlantic and Pacific values taken from the most reliable and recent sources. This is a departure from TRS 247, in which North Atlantic values were preferentially used. The dissolved concentrations were based on either analysis of filtered samples of sea water or, for trace constituents, analysis of the acid soluble fraction of unfiltered samples of sea water. For aluminum, iron and manganese the concentrations given in Table I are those resulting from analysis of filtered samples of sea water, as unfiltered sea water contains significant additional colloidal and fine particulate contributions of these elements.

The detailed calculation was as follows. The concentrations of the elements in pelagic clay (column 4), pelagic carbonate sediments (column 5) and mean shales (column 6) were derived from Bowen [55]. The ratio of the concentration of an element in pelagic clays to that in deep ocean water provides one estimate of the K_d (column 8) for the element. Several authors have reported marine elemental mass balances, and the partitioning of elements between various marine phases was determined on this basis [56, 58, 77–81]. However, for the purpose of deriving suitable K_ds for use in oceanographic and radiological models applied to the transport of radioactive waste, an estimate of the wholly exchangeable particulate phase component is needed. This was estimated from the difference between the total pelagic clay element concentration and the source rock abundance. Where this difference is positive it has been assumed to be a measure of the augmentation of pelagic clays by authigenic components during transport between weathering and sedimentation. In very few cases does the crude estimate of potentially exchangeable element concentration depend on whether shale or mean crustal abundances have been used to subtract detrital (crystalline) phase concentrations from total pelagic clay concentrations; such cases are those of selenium, mercury and thallium. For all three, the mean crustal abundance provides the greater estimate of exchangeable phase concentration. The mean shale was used as the basis for assessing pelagic clay enrichment. Where the difference between pelagic clay and mean shale concentrations is positive, suggesting that pelagic clay sediments are enriched over source rock abundance, the difference is shown in column 7 of Table I. This value was subsequently divided by the seawater concentration to yield a value of K_d based on potential pelagic clay enrichment (column 9). Where the difference between pelagic clay and source rock abundance is zero or negative, no entry appears in column 7 and the estimate of the K_d is provided by dividing the total pelagic clay concentration by the seawater concentration (column 8).

The recommended K_ds for elements that are primary constituents of calcareous biogenic material (Ca, Sr, Ba, Ra and U) were derived from the K_ds based on potential carbonate exchange (column 10), which were determined from the ratio of the concentrations in calcareous pelagic sediments (column 5) to those in deep pelagic water (column 3). A K_d is also provided in column 10 for carbon, based on the ratio of carbon in carbonaceous sediments to that in dissolved organic and carbonate forms in sea water.

2.2.2. Alternative derivation of K_ds: review of published data

Experimental and field data published in the literature were reviewed to compare them with the K_ds derived using the methodology described in Section 2.2.1 and to determine K_ds for those elements for which such a methodology could not be applied. This approach was adopted, in particular, for those nuclides of elements no longer occurring naturally on Earth, which were introduced into the environment from nuclear activities, such as technetium and the transuranics.

Difficulty is frequently experienced in relating K_ds derived under experimentally controlled conditions with those measured using marine environmental samples. The considerable ranges of experimental K_ds reported for some elements [82–88] are often a direct result of variations in the materials and/or procedures adopted. Factors that can significantly influence the apparent K_d include: the solid to liquid ratio; the initial concentrations of tracer and carrier in solution; the pH of the liquid before and after equilibration with the solids; the grain size of the solids; the time allowed for equilibration; the procedure used for separating the two phases (e.g. filtering or decanting); whether samples are shaken or left to stand; the phase(s) used to estimate the K_d (frequently only one phase is measured); loss of tracer on container walls or filters; and competition from other ions in solution. In many cases, particularly those studies related to radionuclide migration through rock and fractured media, lack of control of one or more of the above factors, or use of experimental conditions far removed from those found in the marine environment, hinder the adoption of experimentally derived K_ds for ocean disposal models. Experimentally derived K_ds were therefore only considered whenever few, or no, environmental data exist.

For technetium, the recommended K_d (1×10^2) is based on environmentally derived values from the Irish Sea [71]. Although they may accurately reflect the partitioning between ^{99}Tc and the sedimentary material in that area, the extent to which water and sediments are in equilibrium is not known. It should not be inferred that the K_ds obtained are universally applicable. In particular, the influence of organic material, such as that arising from benthic algae, has not been determined. Early experimental studies suggested that technetium, in either the reduced or oxidized form, generally exhibits a K_d of less than 10 [61–66]. In the absence of further particulate data, it is therefore suggested that the recommended value represents an upper bound in oxic systems.

Neptunium K_ds for suspended sediment in coastal waters of the UK [89, 90] and for sediment pore water in the Irish Sea [71] have been reported. Experimental K_ds for northeast Atlantic calcareous ooze and clay fall within this range [91, 92]. Other reported experimental values, for various substrates, are much lower and are not directly applicable [66, 93, 94].

The recommended K_d for plutonium is for a mixture of oxidation states (i.e. Pu III/IV plus V/VI). A relatively large number of environmental K_ds have been reported from a wide variety of marine, riverine and lacustrine environments, and they consistently fall within the range 1×10^4–1×10^6 [47, 71, 95–107]. There seems to be little justification in extending the range for sensitivity analysis. A large number of experimental determinations have also been made, and with very few exceptions (e.g. approximately 1×10^1–1×10^4 for North Pacific red clays [108]) K_ds fall within the range 1×10^4–1×10^6 [71, 86, 92, 109–114]. The latter range also includes values for calcareous sediments from the northeast Atlantic [71, 92].

Environmental K_ds for americium and curium are given by Pentreath et al. [101, 102], Lovett (unpublished data) [106], Aarkrog et al. [104] and Noshkin (unpublished data) [107]. Few experimental data are available for curium, although Erickson [108] gives values for abyssal red clays. Far more experimental data are available for americium, with most studies reporting values in the range of the field data [86, 92, 108, 113–116].

A default K_d of 1 was assigned to non-reactive elements such as hydrogen, the major elements in sea water (Na, Cl and S) and inert gases (Kr and Xe).

For some elements (Ru, Te, Pm, Dy and Ir) insufficient data are available to calculate K_ds using the methodology described in Section 2.2.1 or to derive K_ds from published data. The recommended K_ds for these elements were chosen to be equal to K_ds for periodically adjacent elements and appear in parentheses in Table I.

From experimental studies it is assumed that trivalent californium behaves like curium and americium [117, 118].

The oceanic distribution of ^{210}Po is influenced by biological recycling in surface waters, and ^{210}Po/^{210}Pb disequilibria have been reported [119]. However, over the whole water column, ^{210}Po and ^{210}Pb are in balance with respect to their partitioning between water and particulate fractions [120], and their respective K_ds should be similar. Ranges of K_d were determined from the data of Brewer et al. [79, 121] and Whitfield and Turner [122]. Ocean margin K_ds for polonium are assumed to be identical to open ocean values.

Protactinium behaves in a similar fashion to thorium in the open ocean. Values for the Panama and Guatemala Basins, and for the North Pacific, have been reported [123, 124]. The K_d appears to correlate with the manganese content, and scavenging is enhanced at ocean margins. Coastal sediment CFs should be similar to those of the open sea.

2.2.3. Maximum and minimum values for open ocean K_ds

Table I provides a single recommended K_d for each element and does not include a range of maximum and minimum values, in contrast to TRS 247. Where a range of values is required, as in the case of conducting a sensitivity analysis for a radiological assessment, different approaches for assigning a K_d range can be used. These include the use of site specific data, choosing an arbitrary range (e.g. maximum and minimum values could be assumed to be a factor of 10 higher and lower than the recommended value (this is supported by available data, see column 10 of Table I)) or the application of a probability distribution of values. Sensitivity analysis should indicate whether more data are required for the assessment.

2.3. OCEAN MARGIN K_ds (TABLE II)

2.3.1. Derivation of ocean margin K_ds

The recommended K_ds for coastal and continental shelf environments for a selected number of elements are listed in column 2 of Table II. In addition, a selection of K_ds based on field observations or laboratory experiments, published in peer reviewed literature, has been compiled and presented for comparative purposes in the last column. The remainder of Table II contains the details from which the majority of recommended values were calculated.

A similar approach was adopted for the calculation of coastal K_ds as had been used for open ocean values in Section 2.2, in this case using open ocean, surface dissolved element concentrations (column 2) based on the most recent reliable sources [76, 127] or coastal water concentrations, whenever available

TABLE II. OCEAN MARGIN K_ds

Element	Recommended K_d value[a]	Seawater concentration[b] (kg/kg)	Coastal sediment concentration (kg/kg)	Mean shale concentration (kg/kg) [55]
H	1×10^{0}	1.1×10^{-1} [1]	—	—
C	1×10^{3}	7.2×10^{-6} [125]	1.0×10^{-2} [126]	1.4×10^{-2}
Na	1×10^{-1}	1.1×10^{-2} [1]	—	5.9×10^{-3}
S	5×10^{-1}	9.0×10^{-4} [1]	—	2.4×10^{-3}
Cl	3×10^{-2}	1.9×10^{-2} [1]	—	1.6×10^{-4}
Ca	5×10^{2}	4.1×10^{-4} [1]	—	1.6×10^{-2}
Sc	5×10^{6}	5.0×10^{-13} [127]	—	1.3×10^{-5}
Cr	5×10^{4}	1.7×10^{-10} [127]	4.1×10^{-5} [128]	9.0×10^{-5}
Mn	2×10^{6}	1.0×10^{-10} [127]	7.6×10^{-4} [128]	8.5×10^{-4}
Fe	3×10^{8}	2.2×10^{-11} [127]	3.6×10^{-2} [128]	4.8×10^{-2}
Co	3×10^{5}	1.5×10^{-11} [126, 131]	2.2×10^{-5} [128]	1.9×10^{-5}
Ni	2×10^{4}	3.0×10^{-10} [131, 133, 134]	2.9×10^{-5} [128]	6.8×10^{-5}
Zn	7×10^{4}	2.8×10^{-10} [126, 131, 133]	1.0×10^{-4} [128]	1.2×10^{-4}
Se	3×10^{3}	4.0×10^{-11} [127]	—	5.0×10^{-7}
Kr	1×10^{0}	2.1×10^{-10} [60]	—	—
Sr	8×10^{0}	8.0×10^{-6} [60]	3.0×10^{-4} [136]	3.0×10^{-4}
Y	9×10^{5}	4.7×10^{-12} [60]	2.0×10^{-5} [136]	4.1×10^{-5}
Zr	2×10^{6}	6.8×10^{-12} [127]	8.0×10^{-5} [136]	1.6×10^{-4}
Nb	8×10^{5}	4.7×10^{-12} [60]	—	1.8×10^{-5}
Tc	1×10^{2}	—	—	—
Ru	4×10^{4}	5.0×10^{-15} [60]	—	—
Pd	6×10^{3}	1.9×10^{-14} [127]	—	—
Ag	1×10^{4}	1.0×10^{-13} [126, 138]	—	7.0×10^{-8}
Cd	3×10^{4}	8.0×10^{-12} [126, 133, 138]	1.3×10^{-6} [128]	2.2×10^{-7}
In	5×10^{4}	2.2×10^{-13} [127]	—	5.7×10^{-8}
Sn	4×10^{6}	1.1×10^{-12} [127]	2.4×10^{-5} [128]	6.0×10^{-6}
Sb	2×10^{3}	1.6×10^{-10} [127]	—	1.5×10^{-6}
Te	(1×10^{3})	1.6×10^{-13} [127]	—	—
I	7×10^{1}	5.8×10^{-8} [60]	—	1.9×10^{-5}
Xe	1×10^{0}	3.9×10^{-11} [60]	—	—
Cs	4×10^{3}	3.1×10^{-10} [127]	—	5.5×10^{-6}
Ba	2×10^{3}	5.5×10^{-8} [140]	5.8×10^{-4} [125, 142]	5.5×10^{-4}
Ce	3×10^{6}	6.3×10^{-12} [127]	—	9.6×10^{-5}

Mean crustal concentration (kg/kg) [55]	Coastal sediment concentration based on 20% exchangeable phase (kg/kg)	Ocean margin K_d	K_d based on carbonate exchange	Other derived K_ds
—	—	—	—	—
4.8×10^{-4}	1.0×10^{-2}	1.4×10^{3}	—	—
2.3×10^{-2}	1.2×10^{-3}	1.1×10^{-1}	—	—
2.6×10^{-3}	4.8×10^{-4}	5.3×10^{-1}	—	—
1.3×10^{-4}	3.2×10^{-5}	1.7×10^{-3}	—	—
4.1×10^{-2}	3.2×10^{-3}	7.8×10^{0}	4.9×10^{2}	—
1.6×10^{-5}	2.6×10^{-6}	5.2×10^{6}	—	—
1.0×10^{-4}	8.2×10^{-6}	4.8×10^{4}	—	—
9.5×10^{-4}	1.5×10^{-4}	1.5×10^{6}	—	1×10^{3}–1×10^{6} [129]
4.1×10^{-2}	7.2×10^{-3}	3.3×10^{8}	—	1×10^{5}–1×10^{7} [129, 130]
2.0×10^{-5}	4.4×10^{-6}	2.9×10^{5}	—	1×10^{4}–2.7×10^{5} [47, 57, 132]
8.0×10^{-5}	5.8×10^{-6}	1.9×10^{4}	—	1×10^{3}–1.6×10^{4} [129, 130]
7.5×10^{-5}	2.0×10^{-5}	7.2×10^{4}	—	1×10^{4}–1×10^{6} [129, 130, 135]
5.0×10^{-8}	1.0×10^{-7}	2.5×10^{3}	—	—
—	—	—	—	—
3.7×10^{-4}	6.0×10^{-5}	7.5×10^{0}	2.5×10^{2}	2×10^{0}–3×10^{2} [47, 57]
3.0×10^{-5}	4.0×10^{-6}	8.5×10^{5}	—	—
1.9×10^{-4}	1.6×10^{-5}	2.4×10^{6}	—	—
2.0×10^{-5}	3.6×10^{-6}	7.7×10^{5}	—	—
—	—	—	—	2×10^{2}–5×10^{3} [71, 137] (see Table I)
1.0×10^{-9}	2.0×10^{-10}	4.0×10^{4}	—	—
6.0×10^{-10}	1.2×10^{-10}	6.3×10^{3}	—	—
7.0×10^{-8}	1.4×10^{-8}	1.4×10^{4}	—	1×10^{4}–1×10^{6} [135, 139]
1.1×10^{-7}	2.6×10^{-7}	3.3×10^{4}	—	1×10^{4}–1×10^{5} [129, 130]
4.9×10^{-8}	1.1×10^{-8}	5.2×10^{4}	—	—
2.2×10^{-6}	4.8×10^{-6}	4.4×10^{6}	—	—
2.0×10^{-7}	3.0×10^{-7}	1.9×10^{3}	—	—
5.0×10^{-9}	1.0×10^{-9}	6.3×10^{3}	—	—
1.4×10^{-7}	3.8×10^{-6}	6.6×10^{1}	—	—
—	—	—	—	—
3.0×10^{-6}	1.1×10^{-6}	3.5×10^{3}	—	3×10^{2}–2×10^{4} [42, 47, 57, 132]
5.0×10^{-4}	1.2×10^{-4}	2.1×10^{3}	9.5×10^{3}	—
6.8×10^{-5}	1.9×10^{-5}	3.0×10^{6}	—	—

TABLE II. (cont.)

Element	Recommended K_d value[a]	Seawater concentration[b] (kg/kg)	Coastal sediment concentration (kg/kg)	Mean shale concentration (kg/kg) [55]
Pm	(2×10^{6})	—	—	—
Pr	5×10^{6}	4.9×10^{-13} [127]	—	1.1×10^{-5}
Sm	3×10^{6}	4.7×10^{-13} [127]	—	7.0×10^{-6}
Eu	2×10^{6}	1.1×10^{-13} [127]	—	1.2×10^{-6}
Gd	2×10^{6}	6.0×10^{-13} [127]	—	6.0×10^{-6}
Tb	2×10^{6}	1.0×10^{-13} [127]	—	1.0×10^{-6}
Dy	1×10^{6}	7.8×10^{-13} [127]	—	5.8×10^{-6}
Tm	1×10^{6}	1.1×10^{-13} [127]	—	6.0×10^{-7}
Yb	1×10^{6}	5.9×10^{-13} [127]	—	3.9×10^{-6}
Hf	1×10^{7}	5.4×10^{-14} [127]	—	2.8×10^{-6}
Ta	2×10^{5}	2.0×10^{-12} [127]	—	2.0×10^{-6}
W	3×10^{4}	1.1×10^{-11} [60]	—	1.9×10^{-6}
Ir	(1×10^{5})	1.7×10^{-15} [127]	—	—
Hg	4×10^{3}	1.0×10^{-11} [142]	2.2×10^{-7} [128]	1.8×10^{-7}
Tl	2×10^{4}	1.0×10^{-11} [60]	—	1.2×10^{-6}
Pb	1×10^{5}	3.0×10^{-11} [133, 138, 142]	2.0×10^{-5} [142]	2.3×10^{-5}
Po	(2×10^{7})	2.7×10^{-18} [145]	—	—
Ra	2×10^{3}	3.3×10^{-16} [146]	—	1.1×10^{-12}
Ac	2×10^{6}	—	—	—
Th	3×10^{6}	7.4×10^{-13} [76]	—	1.2×10^{-5}
Pa	(5×10^{6})	4.4×10^{-18} [76]	—	—
U	1×10^{3}	3.2×10^{-9} [60]	2.0×10^{-5} [136]	3.7×10^{-6}
Np	1×10^{3}	—	—	—
Pu	1×10^{5}	—	—	—
Am	2×10^{6}	—	—	—
Cm	2×10^{6}	—	—	—
Bk	2×10^{6}	—	—	—
Cf	2×10^{6}	—	—	—

[a] Values in parentheses indicate that the recommended K_ds were chosen to be equal to the K_ds of periodically adjacent elements.

[b] Values represent open ocean surface water concentrations, except for elements exhibiting major differences in coastal waters. In these cases coastal water concentrations were used.

Mean crustal concentration (kg/kg) [55]	Coastal sediment concentration based on 20% exchangeable phase (kg/kg)	Ocean margin K_d	K_d based on carbonate exchange	Other derived K_ds
—	—	—	—	2×10^6–1×10^7 [141]
9.5×10^{-6}	2.2×10^{-6}	4.5×10^6	—	—
7.9×10^{-6}	1.4×10^{-6}	3.0×10^6	—	—
2.1×10^{-6}	2.4×10^{-7}	2.2×10^6	—	—
7.7×10^{-6}	1.2×10^{-6}	2.0×10^6	—	—
1.1×10^{-6}	2.0×10^{-7}	2.0×10^6	—	—
6.0×10^{-6}	1.2×10^{-6}	1.5×10^6	—	—
4.8×10^{-7}	1.2×10^{-7}	1.1×10^6	—	—
3.3×10^{-6}	7.8×10^{-7}	1.3×10^6	—	—
5.3×10^{-6}	5.6×10^{-7}	1.0×10^7	—	—
2.0×10^{-6}	4.0×10^{-7}	2.0×10^5	—	—
1.0×10^{-6}	3.8×10^{-7}	3.5×10^4	—	—
3.0×10^{-12}	6.0×10^{-13}	3.5×10^2	—	—
5.0×10^{-8}	4.4×10^{-8}	4.4×10^3	—	4×10^4–1.6×10^5 [143]
6.0×10^{-7}	2.4×10^{-7}	2.4×10^4	—	—
1.4×10^{-5}	4.0×10^{-6}	1.3×10^5	—	3×10^3–1×10^7 [129, 130, 135, 144]
—	—	—	—	—
6.0×10^{-13}	2.2×10^{-13}	6.7×10^2	2.9×10^4	—
—	—	—	—	—
1.2×10^{-5}	2.4×10^{-6}	3.2×10^6	—	1×10^4–1×10^7 [141, 144, 147]
—	—	—	—	—
2.4×10^{-6}	4.0×10^{-6}	1.3×10^3	—	1×10^3 [141]
—	—	—	—	5×10^3–1×10^4 [144, 148]
—	—	—	—	4×10^5 [141]
—	—	—	—	2×10^6 [141]
—	—	—	—	1×10^6 [148]
—	—	—	—	—
—	—	—	—	2×10^4–1×10^5 [117]

[125, 126, 142]. Many more K_ds have been obtained by direct measurement in coastal environments, and these studies provide a valuable source of data. However, this does not apply to the entire suite of elements required for radiological assessment purposes. In addition, coastal sediments generally are very heterogeneous, in terms of grain size and mineralogy, and data obtained from a single location are not necessarily universally applicable.

Concentrations in near shore sediments for 16 elements (C, Cr, Mn, Fe, Co, Ni, Zn, Sr, Y, Zr, Cd, Sn, Ba, Hg, Pb and U) were derived from published values [128, 136 149–151] (column 4). With few exceptions, these values were found to be within a factor of 2 of the mean shale concentrations (column 5) taken from Bowen [55]. Sedimentary concentrations for the remaining elements were then taken from a compilation of mean shale compositions. For ruthenium, lead, tellurium and iridium, mean concentrations in continental crust (column 6) were used. While this is an arbitrary procedure, it should provide values for the concentration of the elements in coastal sediment silts and clays that are well within an order of magnitude of the real values in all cases.

The next challenge was to represent the average bulk composition of coastal sediments and estimate the exchangeable (or non-detrital) proportions of the elements in these sediments. The bulk composition of coastal sediments varies widely from essentially zero silt–clay to 100% silt–clay. The average coastal zone sediment might comprise 50% fine and 50% coarse (sand sized and coarser) material, but no firm average can be chosen. The proportion of the total elemental abundance in coastal sediments that is exchangeable with the aqueous phase is equally difficult to determine. Estimates of the proportions of metals, for example, that are present in easily leachable fractions of sediment vary widely according to both the bulk composition of the matrix and the chemical extraction methodologies. Nevertheless, in fine (pelitic) sediments, substantial proportions of some elements, namely manganese, cadmium, zinc and copper, are found to be easily solubilized by weak acids. The avenue taken to resolve these two problems was to assume for all elements except carbon that 20% of the total concentration of the elements in pelitic coastal sediments (clays and silts) represents the exchangeable phase components of the elements. This arbitrary choice is intended to take into account both the varying proportions of coarse material (which is not generally involved in exchange processes) in coastal sediments and the proportion of the elements associated with pelitic fractions available for exchange with the aqueous phase. For carbon, it has been assumed that the sediments are largely pelitic and that all the associated carbon is available for exchange with carbon in the dissolved phase.

The estimates of mean exchangeable sedimentary abundances of the elements (column 7) were then divided by the coastal water concentrations to provide K_ds for coastal sediments (column 8).

Values of K_d on exchange with calcareous material were also calculated for calcium, strontium, barium and radium using the pelagic carbonate concentrations given in Table I (column 5) and are provided in column 9 of Table II. Only the recommended K_d for calcium, however, is derived from the value based on carbonate exchange, since most of the material in the coastal zone is terrigenous in origin.

2.3.2. Alternative derivation of ocean margin K_ds: review of published data

Experimental and field data published in the literature were reviewed to compare them with the K_ds derived using the methodology described in Section 2.3.1 and to determine K_ds for those elements for which such a methodology could not be applied.

Variation in marine K_ds can occur as a result of a number of factors, including particle size, the formation of colloidal complexes and iron and manganese coatings on particle surfaces. Such coatings tend to mask the influence of mineralogy. Changes in redox chemistry, which can occur near the sediment–water interface and in poorly ventilated deep basins (e.g. fjords), also influence the adsorption–desorption of redox sensitive elements such as cobalt, manganese [152] and plutonium [153]. Detailed site specific investigations can be of benefit, particularly when attempting to provide more realistic model predictions, or for situations in which radioecological data are limited (e.g. the Arctic). Studies with an appropriate experimental design can provide useful information on which factors may be critical in particular circumstances, or for situations in which it would be impractical to collect in situ data.

The impetus to improve the marine K_d database diminished following the cessation of deep ocean disposal in 1983. However, there has been renewed interest in Japan, in relation to both coastal discharges [152] and radioactive waste dumping by the Russian Federation and the FSU in the Sea of Japan [137]. In addition, revelations about the dumping of radioactive waste in the Kara Sea and the Barents Sea [20] by the Russian Federation and the FSU led to the establishment of the IASAP by the IAEA [154]. The K_ds recommended in TRS 247 were used in the preliminary assessment, although efforts were made to provide more realistic values for some of the key model parameters. Site specific K_ds for the principal radionuclides of concern were derived from uptake experiments using sediment collected from two bays (Abrosimov and Stepovogo) used extensively as dump sites off the coast of Novaya Zemlya [46]. The variables selected were salinity and suspended sediment concentration (mg/L). The authors concluded that the salinity changes observed in the two bays would have a minimal impact on the K_ds of the radionuclides studied and that K_d was inversely proportional to the sediment loading, a phenomenon observed in other experimental studies. The study did reveal some apparent differences between the sorption characteristics of sediments from the two bays that might warrant further study. The measured K_ds for caesium, cadmium and americium fell within the IAEA recommended range, although the mean values for all the radionuclides studied fell below the IAEA recommended mean.

Many more measurements of ^{99}Tc in sea water of the Irish Sea and the North Sea have been made as a result of increased discharges from Sellafield in the mid-1990s. These measurements support the notion that ^{99}Tc is conservative in sea water, lending credibility to the few experimental studies that have been reported [155]. In contrast, the very limited particulate analyses reported in the literature [71] suggest K_ds in the range 1×10^2–1×10^3. The lack of particle characterization means that a possible contribution of organic debris cannot be discounted. However, there is growing evidence that ^{99}Tc can be present as a reduced form in anoxic sediments and in poorly ventilated water bodies [156]. This form is more particle reactive, and the use of higher K_ds may be justified in such situations.

In a 1992 investigation of Irish Sea sediments, MacKenzie et al. [157] concluded that K_ds for ^{137}Cs within the seabed were in the range 1×10^4–1×10^5, on the basis of the observed ^{137}Cs/^{241}Am ratios in three sediment cores. The authors suggested that these higher values, well outside the IAEA compilation range, might have been due to differences in the sediment phase composition compared with the overlying suspended particulate material. This suggestion was supported by an experimental study in which contaminated intertidal and salt marsh sediment, from the Solway Firth, north of Sellafield, were subjected to a variety of desorption conditions. The desorption K_d for ^{137}Cs was of the order of 1×10^5. The authors concluded that a more labile fraction of ^{137}Cs had been removed prior to on-shore particulate transport. Differences between adsorption and desorption K_ds in batch experiments have been reported elsewhere [152]. It would be prudent to extend the range of recommended ^{137}Cs K_ds up to 1×10^5 for the modelling of seabed sources.

Recent water column measurements [158, 159] have confirmed the validity of the TRS 247 recommended range of values for plutonium and americium, although in the former study the estimated range of K_ds ($\sim 1 \times 10^4$ to $\sim 7 \times 10^4$) was significantly lower than previously published values.

No attempt has been made to update the previously recommended K_ds for curium, berkelium and californium. The recommended K_ds for tellurium, promethium and iridium were chosen to be equal to K_ds for periodically adjacent elements in accordance with TRS 247 and appear in parentheses in Table II. Finally, a default K_d of 1 was assigned to non-reactive elements such as hydrogen and inert gases (Kr and Xe).

2.3.3. Maximum and minimum values for ocean margin K_ds

Similarly to Table I, Table II provides a single recommended K_d for each element and does not include a range of maximum and minimum values, in contrast with TRS 247. Where a range of values is required, as in the case of conducting a sensitivity analysis for a radiological assessment, different approaches for assigning a K_d range can be used. These include using site specific data, choosing an arbitrary range (e.g. maximum and minimum values could be assumed to be a factor of 10 higher and lower than the recommended value) or applying a probability distribution of values. Sensitivity analysis should indicate whether more data are required for the assessment.

2.4. ESTUARIES: A SPECIAL CASE

Estuaries tend to be very dynamic systems with a high degree of temporal and spatial variability in factors such as pH, salinity, dissolved organic carbon (DOC) and turbidity. High levels of DOC can lead to relatively low lead and plutonium K_ds [160]. Particulate attached plutonium may be released upon contact with low pH river water [161]. Biological recycling in estuarine intertidal sediments can lead to the formation of organoliths composed of iron and manganese deposits with a relatively high radionuclide content that will show seasonality in their abundances [162]. Equilibrium is at best transitory in such systems, and this should be recognized in any modelling and assessment work. A further complication is the preservation in estuaries of hot particles, where these have been present in the original discharges, as has been the case with the Sellafield and Dounreay reprocessing plant discharges. These can be defined as discrete clusters of radioactivity measured using some form of autoradiographic detector (e.g. CR-39 for alpha activity). Assinder et al. [163] reported a wide range of K_ds based on in situ measurements at different tidal states from the Esk Estuary close to the Sellafield outfall, illustrating the non-equilibrium nature of such systems. If such sophistication can be justified, mathematical treatments can be applied that may reduce some of the variability in K_ds, provided data on the temporal and spatial distribution of contributory factors (e.g. salinity, pH and DOC) are available [164].

3. CONCENTRATION FACTORS FOR BIOLOGICAL MATERIAL

3.1. BASIC DERIVATION

The quantity of an element or radionuclide in biological tissue is almost always discussed in terms of concentration, either on a dry or wet weight basis. For modelling purposes, this value is then usually represented in terms of a concentration relative to that of the ambient sea water, traditionally expressed as a CF. If both biological material and seawater concentrations are derived per unit mass, this term is dimensionless:

$$\text{CF (dimensionless)} = \frac{\text{Concentration per unit mass of organism (kg/kg or Bq/kg wet weight)}}{\text{Concentration per unit mass of sea water (kg/kg or Bq/kg)}}$$

In some instances the seawater concentration is derived in terms of unit volume; the CF is then expressed in L/kg, but this makes, numerically, little difference to the CF thus derived:

$$\text{CF (L/kg)} = \frac{\text{Concentration per unit mass of organism (kg/kg or Bq/kg wet weight)}}{\text{Concentration per unit volume of sea water (kg/L or Bq/L)}}$$

For practical purposes, such as in studies with plankton, the concentration in the biological material may also be derived in terms of unit volume. Unless otherwise noted, all values herein relate to wet weight.

The CFs (in L/kg) presented in this report were calculated using the best available compilation of concentrations in filtered sea water. These data were generated using ultra-clean sampling and analytical protocols. We consider both surface and deep bottom water concentrations, depending upon the type of organism. For organisms on the continental shelf (water depths of less than 200 m), an average of Atlantic and Pacific surface water concentrations was used. The operational definition of ‘dissolved’ is typically ‘less than 0.45 μm’. However, it is recognized that metals that fall into this dissolved category may be complexed with organic matter or associated with colloidal particles that may or may not be available for biological uptake. Furthermore, bioavailability can be strongly dependent upon the speciation of the metals where the free metal ion is commonly believed to be the bioavailable form. It is outside the scope of this study to consider the speciation of the metals in the dissolved phase and therefore all metal in the dissolved phase is essentially presumed to be in one pool.

Some confusion may arise from the different terminology used in the literature. Bioaccumulation factors of elements are analogous to bioconcentration factors, except that the former are defined as grams element per gram tissue (or whole organism) divided by grams element per gram water (dissolved plus particulate). In this case, the total water contains both dissolved element and element bound to suspended particulate matter. Since particle loads in oceanic systems are typically low (less than 1 mg/L), total and dissolved element concentrations are very nearly identical, even for particle reactive metals. Differences can become pronounced, however, for particle reactive metals in turbid coastal waters, where extreme particle loads of tens of mg/L can occur.

It should also be noted that, except for algae, the term CF as used in these circumstances does not imply that all the elements within the organism are concentrated by direct accumulation from the water. It is simply a value that relates the concentration in the organism, which may have been derived by uptake from sea water, particulate matter and food, to that of the medium in which it lives.

The term is also used by radiobiologists studying the accumulation of radionuclides by organisms under controlled laboratory conditions, usually that of direct uptake from sea water. In some experiments, the results obtained are similar to those derived from environmental data; in others they are not. There are many reasons for such discrepancies, and these are often the subjects of investigation. It is therefore potentially misleading to use laboratory derived data uncritically, and, wherever possible, environmentally derived data have been used in this report, although these may be equally varied for a number of reasons, and often environmental CF data are simply lacking for certain elements.

3.2. FACTORS AFFECTING CFs

A number of factors must be considered in evaluating the applicability of CFs in marine organisms. The preponderance of data on metal and radionuclide concentrations in marine organisms is based on work with organisms from temperate ecosystems. Only recently have attempts been made to measure metal concentrations in polar organisms, and some attempts have begun to compare temperate and polar CFs. Given the limited data available on this issue, all conclusions must be considered preliminary. However, studies suggest that, as a rule, differences between polar and temperate zone CFs are not pronounced [165, 166]. There is a striking lack of reliable data on metal and radionuclide concentrations in tropical ecosystem organisms, and extrapolation of temperate ecosystem data sets to tropical regions must also be performed with appropriate caution. Metabolic rates and food web complexity can be very different between tropical and temperate regions, and these factors can greatly affect the extent to which metals are concentrated in organisms, particularly for metals accumulated principally via trophic transfer. Seasonal variation in the biological uptake of metals may be great, particularly in polar and temperate regions, where metabolic rates vary appreciably between winter and summer. Relatively little effort has been made to quantify the seasonal variation in metal CFs in marine organisms. For all these reasons the tabulations of CFs presented in this report should be considered first estimates, but not, as yet, a complete data set.

As with metal K_ds, the oxidation state of redox metals (Mn, Co, Cr, Se, Tc, Pu, Fe and others) can complicate the interpretation of data. The particle reactivity and bioavailability of certain metals in sea water may differ greatly with oxidation state (e.g. Cr(VI) versus Cr(III), Se(IV) versus Se(VI), Pu(III) versus Pu(V)). Further, the oxidation state of some metals may change upon association with an organism or particle, rendering those metals much less available for release from the organism or particle. Hence the underlying assumption of exchangeability in considering CFs is not met for these metals.

The relationship between the concentration of an element or radionuclide in a living organism and the ambient sea water is a dynamic one. Rates of both uptake and excretion are known to be affected by body size, rate of change of body size, temperature, light (in the case of algae), salinity, etc. A number of elements that are accumulated by some organisms are not subsequently eliminated, with a variable fraction being virtually permanently incorporated into some parts of the body structure. Skeletal tissues may act as depositories for a number of elements, particularly multivalent cations. Some elements become incorporated into granules, probably as a means of detoxification, which may or may not be subsequently excreted. Crustaceans, which grow by a process of moulting, may lose absorbed material in cast moults as well as resorbing, before moulting, certain other elements that are then reincorporated into the new exoskeleton.

Added to these factors is the continuing change in the concentration of some elements or radionuclides (in coastal waters) over short periods of time. It is to be expected, therefore, that real differences exist between some CFs, even for the same element and species, and that the variability in the data reflects true environmental fluctuations in any one area.

In considering the CFs compiled in this report, it is important to realize that an assumption underlying these values is that organisms are in equilibrium with their ambient sea water with respect to element concentrations. Thus the rates of biological uptake and release of an element or radionuclide are not considered in this report. However, under certain circumstances (such as a spill or periodic discharge), risk assessment exercises may wish to focus on the kinetics of uptake into or out of organisms. The rates of uptake into marine organisms and the uptake pathways (e.g. dietary versus solute uptake) are outside the scope of this report and should be considered separately.

3.3. TABULATED VALUES: GENERAL REMARKS

The tabulated values represent an attempt to update those published in TRS 247, but a full review of the very large amount of data available has not been possible. The values required are those that relate concentrations in marine foodstuffs to those of sea water. Some subjective judgements have been made as to which parts of a marine organism, and in what proportions, are likely to be consumed by humans; these are explained in the following sections.

In making such an update, emphasis has been given to revising those values that were previously derived as best guess estimates and for which data are now available, those values which appeared to have particularly low or high CFs, those materials most likely to be consumed and those radionuclides considered of particular significance in view of their half-lives, expected mobility or likely abundance in nuclear waste. For many elements, a full revision has not been possible and, by default, the values published in TRS 247 have been retained as current best estimates.

As a general rule, literature concentrations expressed as dry or freeze dried weights were converted to wet weight concentrations by multiplying by 0.18. Concentrations normalized to ash sample weights were converted to wet weight concentrations by multiplying by 0.01. Of particular value were the data compiled by Bowen [55], Eisler [167], Phillips [168], Coughtrey and Thorne [169–171] and Jackson et al. [172]; use was also made of the text of Vinogradov [173]. Where necessary, stable element data in organisms were divided by the coastal water concentrations given in Table II. A number of values, of course, were also based entirely on radionuclide results. Methods employed to estimate values where data were inadequate or could not be obtained are described in the notes to the tables. As with sediment K_ds, the default CFs for hydrogen, inert gases (Kr and Xe) and sodium in fish were taken to be 1.

Some comments are warranted on the variability of the data in compiling biological CFs. Generally, insufficient reliable data are available to allow accurate assessments of ranges around a recommended value for most element–organism combinations. Where a reliable database does exist for a given element and type of organism, in nearly every case the range of minimum and maximum CFs is one order of magnitude (or less) from the recommended value. Consequently, the ranges of CFs around recommended values are not included in this report. For those few elements for which reliable data indicate that greater variability is apparent for a given CF, comments are provided in the notes. Where greater variability exists, it is almost always for elements for which the uptake is actively mediated by the organism rather than for elements that are passively adsorbed. This is generally the case for elements with known biological functions, for example as blood pigments, electron transport chain components or enzyme cofactors, and the great variability reflects widely divergent requirements for the element in question among organisms. In some cases organisms actively transport non-essential elements through other element uptake pathways; for example, selenium uptake is an active, enzymatically mediated process in phytoplankton, and different types of phytoplankton have greatly varying requirements for this element, with CFs varying by four orders of magnitude. Similarly, technetium accumulation in macroalgae and crustaceans, iron accumulation in diverse organisms and other elements can display a variability of a few orders of magnitude around the recommended values. These exceptions have been noted where they are known to exist. Thus, except where noted, models can assume that maximum and minimum CFs are one order of magnitude above and below the recommended value.

3.3.1. Comments on carbon and lead

There are two elements upon which some general comments are necessary, namely carbon and lead. For the former, although concentrations of carbon in marine organisms have been accurately determined, a major difficulty arises with regard to selecting the appropriate seawater value as a denominator. In calculations for all other elements the total concentration of the element dissolved in sea water (filtrate) was used. If the same assumption is made with respect to carbon, this includes dissolved organic carbon, carbonate, bicarbonate and CO_2. There are insufficient data to indicate what fraction, if any, would not equilibrate with ^{14}C and to what extent any of the forms of carbon would or would not become biologically incorporated. It was therefore decided to adopt the value based on organic carbon in sea water given in Table II in order to be consistent. The wet weight tissue values for carbon were 95 g/kg for fish, 80 g/kg for crustaceans and molluscs, 65 g/kg for benthic algae, 80 g/kg for zooplankton and 45 g/kg for phytoplankton [55].

With regard to lead, there are again many data in the literature, the majority having been derived from contaminated environments and for which local seawater values were not obtained. There has been considerable debate over the lengths to which it is necessary to go in order to derive accurate lead concentrations in both biological material or sea water. When extensive precautions have been taken, the values obtained away from contaminated areas [174] are very much lower than those derived by other workers. In deriving CFs for lead, therefore, only data on ^{210}Pb have been used, unless otherwise indicated.

3.3.2. Surface water fish (Table III)

The relevant CFs are those relating concentrations in the food substance to those of ambient sea water; consideration therefore has to be given to the fraction of the organism consumed. For fish this usually consists of fillets: muscle plus, possibly, some skin. When such fillets are commercially prepared they are often contaminated by, for example, gut contents and other organs such as liver and kidney; portions of bone might also be included. When chemical analyses are made, however, fish are usually quite carefully dissected. Since the concentrations of many elements differ markedly from one organ to another, with muscle usually having one of the lowest concentrations, quite different results in the apparent concentration of an element in the edible portion can be obtained. Such differences resulting from analyses of laboratory and commercially derived fish samples for plutonium analyses have been commented upon by Pentreath et al. [175]. In suggesting a CF appropriate to models used to assess dose to humans, some adjustment (upwards) of the value derived from laboratory prepared samples would appear to be appropriate in some cases, and this has been done. It is also necessary to consider the consequences of the consumption of whole fish, such as anchovies, which would also include gut contents. It would not be realistic to bias all data to allow for continual consumption of nothing but whole fish, but nevertheless some form of adjustment is clearly necessary. Data from a sample of 24 650 people in the USA [176] indicate that less than 0.5% consumed anchovies. If one assumes that the quotient of the whole body CF to flesh CF is Z, the effect of eating 0.5% whole fish would be to adjust the recommended CF in the following manner:

$$\mathrm{CF} = (\mathrm{CF}_{\mathrm{flesh}} \times 0.995) + (\mathrm{CF}_{\mathrm{flesh}} \times 0.005 \times Z)$$

In some cases tinned fish consisting only of flesh and bone is consumed; it may be possible that the bone CF is greater than that of the whole body CF, in which case, in order to be conservative, the recommended CF has been rounded upwards. There are other considerations, such as the consumption of fish gonads (roe), but the data available on their consumption, and separate CFs, are too limited to make any sensible recommendations. Three types of database were considered before a mean value and range were adopted for each element. Consideration was first given to field derived radionuclide concentrations in fish and sea water, including ^{54}Mn, ^{60}Co, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{99}Tc, ^{106}Ru, ^{137}Cs, ^{144}Ce, ^{210}Pb, ^{210}Po[2], ^{226}Ra, ^{232}Th, ^{238}U, ^{237}Np, $^{239/240}$Pu, ^{241}Am and $^{242/244}$Cm. Consideration was then given to data derived from the simultaneous determination of stable elements in fish and water, and finally to tabulated stable element data for fish, with the coastal water stable element estimates given in Table II being used as a denominator. In addition to the general references listed in Section 3.3, the review by Pentreath [177] was used extensively, although in some cases the data were modified in the light of more recent information.

3.3.3. Crustaceans (Table IV)

A variety of crustacean species are taken for human consumption. The muscle portion is the fraction usually consumed; this consists of the ‘tails’ of shrimps, prawns and lobsters, and the limb muscles of crabs. Other tissues are also eaten, however, and are converted into pastes; these tissues consist of hepatopancreas and gonad. The gut and gills are usually removed, and the carapace is not intentionally consumed.

To arrive at a recommended CF for each element it was not considered plausible to make appropriate adjustments for the consumption of these different fractions, and thus the values were derived primarily from whatever ‘soft part’ data were available. The selection criteria were essentially those adopted for the fish values, with emphasis being given to data obtained from simultaneous radionuclide derived water and biological material analyses, simultaneous stable element analyses and finally using the seawater values given in Table II applied to any stable element data in biological material from non-contaminated environments.

3.3.4. Molluscs (Table V)

Gastropod, lamellibranch and cephalopod molluscs are consumed by humans. For gastropods and lamellibranchs the ‘total soft parts’ are the relevant fractions for estimating CFs, and these usually include gut contents, although commercially obtained molluscs may have been held in cleansing tanks before

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[2] It is worth noting that tinned fish has reduced levels of ^{210}Po, compared with freshly caught produce, owing to the decay of unsupported ^{210}Po.

sale. Consumption of cephalopods is somewhat different; this is discussed in Section 3.3.7. The criteria used for selection of the data are essentially those adopted for fish and crustaceans. In general, the values for lamellibranchs and gastropods have been pooled to obtain average values, but it is assumed that more lamellibranchs are taken for human consumption than gastropods.

3.3.5. Macroalgae (Table VI)

Macroalgae (benthic algae) that enter the human diet consist of Rhodophyceae (red), Chlorophyceae (green) and Phaeophyceae (brown) species. Species of red and green algae are directly consumed in many countries, but brown algae are largely taken for conversion into alginates. There are exceptions; some Phaeophyceae are consumed in China, Japan and other Far Eastern countries, but probably not in large quantities. The extent to which radionuclides incorporated into alginates enter the human diet is not known, but for the purposes of this report it is assumed that 10% of the algae appear in alginate products.

By no means are all species, of even red and green algae, consumed; unfortunately, many of the species for which elemental concentration data are available are among those that are not. This includes the genus *Fucus*, which has been extensively studied because of its utility as an 'indicator' organism for many elements, especially metals. There are also marked differences for some elements in the extent to which they are accumulated (by the three groups) relative to the concentrations in ambient sea water. Where such differences are very large and consistent, the recommended CFs have been deliberately biased towards the red and green algae data.

For many elements it must be assumed that the data derived are likely to be influenced by the method of sample collection. Owing to the mucous surface coating in many species, particulate material adheres to the samples and, conversely, the mucilaginous coating often sloughs off after the plant has been removed from sea water. Such factors may influence the wide range of values cited in some of the literature reviews. In selecting the CF data, as with those derived for fauna, emphasis has been given, wherever possible, to those obtained from simultaneously derived plant and seawater (radionuclide and stable element) values.

3.3.6. Plankton: zooplankton and phytoplankton (Tables VII and VIII)

Pelagic organisms that float in the sea and are non-motile, or have limited powers of movement, are collectively called plankton. Planktonic organisms may be either plants (phytoplankton) or animals (zooplankton). Phytoplankton includes many groups; prominent among these are diatoms, dinoflagellates, coccolithopores, green algae and cyanobacteria. Zooplankton is derived from many groups of animals that range in size from about 5 μm to 1 m in diameter. Important groups include copepod crustaceans, euphausiids (krill), cnidarians, ostracod crustaceans, pteropod molluscs, chaetognaths and pelagic tunicates. Many species have an entirely planktonic life history; these constitute the holoplankton. Other organisms, including some of those that otherwise live on or in the seabed, spend only part of their life history in plankton, particularly as eggs and larvae, and these temporary components of plankton are called meroplankton.

Since plankton consists of such a variety of organisms, it was desirable to divide this section into at least phytoplankton and zooplankton. Many of the data in the literature simply refer to either of these two groups without further detail, but it is assumed that most data on zooplankton refer to crustacean forms, unless otherwise specified. In view of the large surface area to volume ratio, a frequent requirement of passively floating pelagic organisms, it is likely that many elements are accumulated by adsorptive processes, and many laboratory derived CF data are in good agreement with estimates made from in situ investigations. A full literature review has not been possible, however, and many of the values recommended have simply been drawn from earlier compilations. With regard to the consumption of plankton by humans, this is usually thought of in terms of harvesting krill, the food of the mysticeti (whalebone) whales. Whalebone whales actually feed on many different types of plankton, although usually some forms predominate in different waters: mysids off Vancouver, golatheids in the Chilean fjords, copepods in the Bay of Fundy. However, the term krill is most universally applied to the Antarctic euphausiid, *Euphausia superba.* This is a large euphausiid, some 6 cm in length when adult. Chemical determinations of this species are few and it is difficult to determine whether the crustacean or zooplankton CFs should be applied. However, as many of the zooplankton values are based on other euphausiids and as plankton harvesting is likely to include other species, it is suggested that the zooplankton CFs are preferable.

3.3.7. Cephalopods (Table IX)

Cephalopods are taken from both surface water and mid-water depths for human consumption. The edible fractions of squid are usually the mantle (from which the viscera have been removed), the head and the tentacles, whereas for octopods it is usually the tentacles only. These edible portions do not therefore contain sedimentary material or those organs that contain high concentrations of many elements; thus they differ from the ‘total soft parts’ of other molluscs in terms of their concentrations of many elements. It is not possible to develop a complete list of CFs for cephalopods, but some values derived for a number of elements are listed in Table IX, and these can be compared with the recommended CFs for fish and other molluscs.

3.3.8. Mesopelagic fish

All the recommended CFs presented in Section 3.3.2 refer to, and are based on, surface water fish data. The extent to which such values can be applied to fish living at depths greater than about 200 m is not entirely clear, and there is certainly an insufficient database to derive a complete separate list of CFs for them. From a brief perusal of the literature, it appears that the concentrations of a number of trace elements (Mn, Fe, Cu and Zn) are not significantly different in mesopelagic and coastal water fish, nor are ^{137}Cs and ^{90}Sr concentrations [178]. The same applies to coastal water and mesopelagic cephalopods. It is therefore suggested that either the surface water fish CFs be used throughout, or that the CF, if applied to deep ocean water, be adjusted in proportion to the ratio of the surface water to deep water elemental concentrations.

3.3.9. Mammals (Tables X–XII)

Marine mammals are considered to be at or near the top of the marine food chain. In addition, many species are consumed by indigenous populations, particularly in the Arctic region. Therefore, in terms of establishing adequate radiation dose models, for the sake of completeness, transfer factors to this link in the marine food chain leading to humans should be included. Radionuclide and trace element data are extremely limited for marine mammals when compared with other marine organisms. Furthermore, the fact that many marine mammals are not in constant contact with water and that they derive most of their radionuclide or trace element burden directly from their food makes the computation of CFs somewhat tenuous. Nevertheless, in order to make relevant comparisons with CFs in other marine species, CFs for mammals have been computed using ambient concentrations of radionuclides and trace elements in the surrounding waters (see notes to the tables). As both muscle and liver are often consumed by humans, where data exist CFs for these two tissues are given. It should be kept in mind that since mammals obtain the majority of their contaminant load from food and some mammals feed at very different levels of the food chain, CFs are likely to vary considerably within any one group of mammals. A good example of such variability is mercury in whalebone whales, which consume plankton, compared with mercury in carnivorous toothed whales. Given the importance of diet, transfer mechanisms through the food chain also probably control the body burdens in other mammal species.

TABLE III. CONCENTRATION FACTORS FOR FISH

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
H	1×10^{0}	1×10^{0}	See Section 3.3
C	5×10^{4}	2×10^{4}	See Section 3.3.1
Na	1×10^{-1}	1×10^{0}	See Section 3.3
S	1×10^{0}	1×10^{0}	F1
Cl	1×10^{0}	6×10^{-2}	F2
Ca	1×10^{0}	2×10^{0}	F3
Sc	—	1×10^{3}	F3
Cr	1×10^{2}	2×10^{2}	F3
Mn	5×10^{2}	1×10^{3}	F3
Fe	1×10^{3}	3×10^{4}	F4
Co	1×10^{2}	7×10^{2}	F5
Ni	5×10^{2}	1×10^{3}	F6
Zn	2×10^{3}	1×10^{3}	F6
Se	1×10^{2}	1×10^{4}	F7
Kr	—	(1×10^{0})	See Section 3.3
Sr	1×10^{0}	3×10^{0}	F8
Y	1×10^{0}	2×10^{1}	F9
Zr	1×10^{0}	2×10^{1}	F10
Nb	1×10^{0}	3×10^{1}	F11
Tc	1×10^{1}	8×10^{1}	F12
Ru	1×10^{0}	2×10^{0}	F13
Pd	(3×10^{2})	(3×10^{2})	F1
Ag	1×10^{3}	1×10^{4}	F14
Cd	—	5×10^{3}	F15
In	—	5×10^{2}	F16
Sn	1×10^{3}	5×10^{5}	F17
Sb	1×10^{3}	6×10^{2}	F18
Te	1×10^{3}	1×10^{3}	F1
I	1×10^{1}	9×10^{0}	F19
Xe	—	1×10^{0}	See Section 3.3
Cs	5×10^{1}	1×10^{2}	F20
Ba	—	1×10^{1}	F21
Ce	(1×10^{1})	5×10^{1}	F22
Pm	1×10^{2}	(3×10^{2})	F23
Sm	(1×10^{2})	(3×10^{2})	F23
Eu	(1×10^{2})	3×10^{2}	F22
Gd	—	(3×10^{2})	F23
Tb	—	6×10^{1}	F22
Dy	—	(3×10^{2})	F23

TABLE III. (cont.)

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
Tm	—	(3×10^2)	F23
Yb	—	2×10^2	F22
Hf	—	5×10^2	F24
Ta	—	6×10^1	F24
W	—	9×10^1	F24
Ir	—	2×10^1	F24
Hg	—	3×10^4	F25
Tl	—	5×10^3	F26
Pb	3×10^2	2×10^2	See Section 3.3.1
Po	2×10^3	2×10^3	F27
Ra	1×10^2	1×10^2	F28
Ac	3×10^1	(5×10^1)	F26
Th	1×10^3	6×10^2	F27
Pa	1×10^1	(5×10^1)	F26
U	1×10^{-1}	1×10^0	F29
Np	(1×10^1)	1×10^0	F30
Pu	1×10^1	1×10^2	F31
Am	1×10^1	1×10^2	F12
Cm	(1×10^1)	1×10^2	F12
Bk	—	(1×10^2)	F32
Cf	(1×10^1)	(1×10^2)	F32

[a] Values in parentheses are best estimates: see Section 3.3.

NOTES TO TABLE III

F1 No new data are available. The CF given in IAEA-TECDOC-211 [179] is therefore recommended.

F2 The recommended CF was derived assuming a concentration of chlorine in fish of 6 g/kg dry weight [55].

F3 Ranges found in the literature allow inclusion of some bone in consumed fish. The adopted concentrations for scandium and manganese were 0.6 μg/kg and 0.1 mg/kg, both wet weight, respectively [167, 177].

F4 Concentrations of iron in fish are very variable because of the blood content of different organs and the types of muscle tissue.

F5 Measurements of ^{60}Co in fish and sea water from the northeast Pacific Ocean [180] and the Marshall Islands [107] suggest that the CF for fish is greater than

1×10^3. There is, however, a significant body of stable element concentrations for cobalt in fish flesh, which average at about 0.01 mg/kg wet weight. This concentration was used to derive the recommended CF.

F6 The range of data is considerable. Concentrations in flesh are likely to be lower than the values used to calculate the CFs in the table for both nickel and zinc, but allowance was made for whole fish consumption.

F7 Concentrations of selenium in flesh vary from 0.1 to 2.0 mg/kg wet weight. An average value of 0.5 mg/kg wet weight was assumed [167].

F8 CFs for flesh for strontium reported in the literature are less than 1. The recommended value allows for bone and whole fish consumption.

F9 Yttrium data give a CF range of 2 to 10 [181]. These values were multiplied by 3.5 to allow for whole fish consumption.

F10 Few data are available for zirconium, indicating a CF for flesh of about 100 [177]. It should be noted, however, that ^{95}Zr is barely detectable in muscle samples from known contaminated areas. Therefore a CF ten times lower seems more reasonable. This CF was then doubled to allow for contamination and consumption of other organs.

F11 The only extensive measurements of concentrations of niobium in fish flesh are those of Schroeder and Balassa [182]. For a variety of species the average concentration was 0.3 mg/kg wet weight. Dividing this number by the estimated niobium coastal water concentration results in an average CF of 6×10^4. If this is indeed the CF, ^{95}Nb should be more than readily detectable in fish from contaminated areas such as the Irish Sea, but it is not [183]. The stable element value was therefore not used. Instead, the zirconium CF was multiplied by 1.5 on the basis that some enhancement of ^{95}Nb over ^{95}Zr has been observed in biological material [184].

F12 The recommended CF was determined using data for the English Channel from the Institut de protection et de sûreté nucléaire (IPSN) [43].

F13 CFs for muscle for ^{106}Ru suggest a range of 0.1 to 1 [177]. Applying a whole fish to muscle ratio of 3.5 a CF of 2 is therefore recommended.

F14 A muscle value of 0.01 mg/kg wet weight for silver is suggested [177], giving a CF of 1×10^4.

F15 Concentrations of cadmium in fish are very variable, many samples analysed having been taken from contaminated waters. The recommended CF was derived using a typical concentration of cadmium in muscle of 0.04 mg/kg wet weight.

F16 The recommended CF for indium is an upper limit based on the mean of detection limits for fish [185].

F17 The recommended CF for tin was derived from concentrations of the stable element [167]; these ranged from 0.2 to 2.0 mg/kg wet weight. A value of 0.5 mg/kg wet weight was selected.

F18 Stable antimony values in fish flesh vary considerably [167]. The recommended CF was derived assuming a concentration of antimony in fish of 0.1 mg/kg wet weight.

F19 The recommended CF was calculated using a concentration of iodine in fish of 0.5 mg/kg wet weight taken from Pentreath [177].

F20 The recommended CF is based primarily on measurements of ^{137}Cs in fish and samples of sea water. The CFs are different for different species taken in the same environment, and variations in concentration with size are also evident [177, 186].

F21 The recommended CF for barium is based on data given in Ewing et al. [185] and Goldberg [187].

F22 Data on CFs for a number of rare earths are reported by Suzuki et al. [188]. For cerium, the average CF derived from muscle analyses was about 300, related to ‘soluble’ cerium concentrations in sea water. It should be noted, however, that ^{144}Ce is not observed in fish samples taken from the Irish Sea, which suggests that the CF is unlikely to be greater than 50 for the consumable portion. In situ data from Japan [189] suggest a value of 50. For the other rare earths (europium, terbium and ytterbium) no in situ data are available and thus the CFs estimated by Suzuki et al. [188] have been retained.

F23 The recommended CFs are conservatively rounded up values based on the highest measured CF for the other rare earth elements (see Note F24).

F24 Average upper limits for concentrations of these elements in fish have been reported by Ewing et al. [185]. The recommended CFs were derived using these values, except for iridium.

F25 The recommended CF was derived using a representative concentration for total mercury in sea water (5 ng/L) from the Persian Gulf and Arabian Sea [142, 190] and a typical total mercury concentration in fish (0.15 μg/g) from the same region [191–193].

F26 No new data are available.

F27 The recommended CF was derived using data taken from Jackson et al. [172].

F28 The recommended CF was derived using the average concentration of ^{226}Ra from all tissues, reported by Jackson et al. [172].

F29 Typical concentrations of uranium in fish flesh of about 0.2 μg/kg wet weight are reported in the literature [177]. The CF derived using this concentration is less than 0.1; it has been increased to 1 to allow for the possible inclusion of some bone in the edible fraction.

F30 The only concentrations of ^{237}Np in environmental samples are those reported by Pentreath and Harvey [89]. An estimated CF for fish flesh, based on these data, is less than 0.01. In view of the uncertainty of this number, a value of 1 is recommended, to allow for whole fish consumption.

F31 A large number of data are available on plutonium in fish tissues, many of which have been summarized [172]. CFs average at 3.5×10^2 [71] and 1×10^2 in the English Channel [43]. A recommended value of 1×10^2 is given.

F32 Data on berkelium and californium in the literature are scarce. The behaviour of berkelium and californium is assumed to be similar to that of americium and curium, and therefore the CFs for americium and curium are recommended for both berkelium and californium.

TABLE IV. CONCENTRATION FACTORS FOR CRUSTACEANS

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
H	1×10^{0}	1×10^{0}	See Section 3.3
C	4×10^{4}	2×10^{4}	See Section 3.3.1
Na	3×10^{-1}	7×10^{-2}	C1
S	3×10^{0}	1×10^{0}	C2
Cl	1×10^{0}	6×10^{-2}	C3
Ca	1×10^{1}	5×10^{0}	C4
Sc	—	3×10^{2}	C5
Cr	5×10^{2}	1×10^{2}	C6
Mn	1×10^{4}	5×10^{3}	C7
Fe	1×10^{3}	5×10^{5}	C8
Co	1×10^{3}	7×10^{3}	C9
Ni	1×10^{2}	1×10^{3}	C10
Zn	4×10^{3}	3×10^{5}	C11
Se	1×10^{3}	1×10^{4}	C12
Kr	—	(1×10^{0})	See Section 3.3
Sr	1×10^{1}	5×10^{0}	C13
Y	1×10^{3}	1×10^{3}	C14
Zr	1×10^{2}	2×10^{2}	C15
Nb	1×10^{2}	2×10^{2}	C15
Tc	1×10^{3}	1×10^{3}	C16
Ru	6×10^{2}	1×10^{2}	C17
Pd	(3×10^{2})	(3×10^{2})	C14
Ag	5×10^{3}	2×10^{5}	C18
Cd	—	8×10^{4}	C19
In	—	1×10^{4}	C20
Sn	3×10^{2}	5×10^{5}	C21
Sb	3×10^{2}	3×10^{2}	C22
Te	1×10^{3}	1×10^{3}	C14
I	1×10^{2}	3×10^{0}	C23
Xe	—	1×10^{0}	See Section 3.3
Cs	3×10^{1}	5×10^{1}	C24
Ba	—	7×10^{-1}	C25
Ce	1×10^{3}	1×10^{3}	C26
Pm	1×10^{3}	(4×10^{3})	C27
Sm	(1×10^{3})	(4×10^{3})	C27
Eu	1×10^{3}	4×10^{3}	C27
Gd	—	(4×10^{3})	C27
Tb	—	(4×10^{3})	C27
Dy	—	(4×10^{3})	C27

TABLE IV. (cont.)

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
Tm	—	(4×10^3)	C27
Yb	—	(4×10^3)	C27
Hf	—	(4×10^3)	C27
Ta	—	2×10^3	C28
W	—	1×10^1	C29
Ir	—	(1×10^2)	C20
Hg	—	1×10^4	C30
Tl	—	(1×10^3)	C20
Pb	1×10^2	9×10^4	C11
Po	2×10^4	2×10^4	C31
Ra	1×10^2	1×10^2	C14
Ac	1×10^3	1×10^3	C14
Th	1×10^3	1×10^3	C14
Pa	1×10^1	1×10^1	C14
U	1×10^1	1×10^1	C14
Np	(1×10^2)	(1×10^2)	C14
Pu	1×10^2	2×10^2	C32
Am	2×10^2	4×10^2	C33
Cm	(2×10^2)	(4×10^2)	C34
Bk	—	(4×10^2)	C34
Cf	(2×10^2)	4×10^2	C35

[a] Values in parentheses are best estimates: see Section 3.3.

NOTES TO TABLE IV

C1 The recommended CF was derived assuming a concentration of sodium in crustaceans of 4 g/kg dry weight [55].

C2 The recommended CF was derived assuming a concentration of sulphur in crustaceans of 6 g/kg dry weight [55].

C3 The recommended CF was derived assuming a concentration of chlorine in crustaceans of 6 g/kg dry weight [55].

C4 The recommended CF was derived assuming a concentration of calcium in muscle tissues of *Nephrops* of 2 g/kg wet weight [194].

C5 The recommended CF was derived using data from Robertson [195].

C6 A CF of 1×10^3 has been reported for ^{51}Cr [196], but an assessment by Swift and Kershaw [197] suggests a lower value of about 1×10^2. The latter value is recommended.

C7 The recommended CF was derived assuming a concentration of manganese in crustaceans of 2.5 mg/kg dry weight.

C8 The recommended CF was derived assuming a concentration of iron in crustaceans of 10 mg/kg wet weight.

C9 The recommended CF was derived assuming a conservative concentration of cobalt in crustaceans of 0.1 mg/kg wet weight.

C10 Data on concentrations of nickel in crustaceans vary considerably; an average concentration of 0.4 mg/kg wet weight was used to derive the recommended CF.

C11 The recommended CF was derived using data from Zauke and Petri [198].

C12 Few data are available on concentrations of selenium in crustaceans. A typical concentration of 0.5 mg/kg wet weight was assumed [167] to derive the recommended CF.

C13 Few data are available on concentrations of strontium in the edible fraction of crustaceans. A typical concentration of 40 mg/kg wet weight was assumed to derive the recommended CF.

C14 No new data are available. The CF given in IAEA-TECDOC-211 [179] is therefore recommended.

C15 No new data are available. Typical in situ ^{95}Zr and ^{95}Nb CFs of 100 are reported [196].

C16 Environmental data on technetium are still few for crustaceans in general, but it is clear from both laboratory experiments and field data that considerable interspecies differences exist [64, 159, 199]. In fact, field studies in the Irish Sea [159] have shown that technetium uptake by lobsters is unique, with CFs averaging 4×10^4. Considerable differences also exist between different tissues of the same organism. Field data from Brown et al. [200] and Swift and Kershaw [197] have been used to derive the recommended value. A value higher than the recommended CF for crustaceans should be used for lobsters.

C17 Environmental data indicate a suitable ^{106}Ru CF for 'edible fractions' to be between 1 and 100. Coughtrey and Thorne [169] suggest a value of 10. Values for muscle tissue are often similar, but viscera are likely to be considerably higher, by more than a factor of 10. A value of 100 is recommended as a suitable average value.

C18 Based on data provided by Eisler [167] and Coughtrey and Thorne [170]: a silver concentration in crustaceans of 0.2 mg/kg wet weight was assumed to derive the recommended CF.

C19 Concentrations of cadmium vary considerably from one tissue to another. This element is particularly accumulated in the hepatopancreas. It appears that crabs tend to accumulate more cadmium than either shrimps or lobsters, and it is recommended to allow for such differences. The recommended CF was derived using data from Zauke and Petri [198].

C20 No new data are available.

C21 Few data are available on concentrations of tin in crustaceans. A typical concentration of 0.5 mg/kg wet weight [167, 171] was assumed to derive the recommended CF.

C22 Data on concentrations of antimony in crustaceans vary considerably. Van Weers and van Raaphorst [201] report an average concentration of antimony of 0.04 kg/kg dry weight in shrimps, but other data range from 0.02 to 10 mg/kg dry weight [167, 171]. Data from Swift and Kershaw [197] were used to derive the recommended CF.

C23 Few recent iodine data are available and there is little to support or refute the concentration of 1 mg/kg dry weight given by Bowen [55]. This concentration was used to derive the recommended CF.

C24 The recommended CF was derived using data from Fisher et al. [166].

C25 The recommended CF was derived assuming a concentration of barium in crustaceans of 0.2 mg/kg dry weight [55].

C26 No new data are available. The CF given in IAEA-TECDOC-211 [179] is therefore recommended. This is probably an upper limit.

C27 Very few data are available on the lanthanides in crustaceans. Fowler [202] gives a value of 2.3 μg/kg dry weight for europium in whole euphausiids; this gives a CF on a wet weight basis of about 4×10^3. CFs for other rare earths, for which no measurements are available, are assumed to be equal to the value for europium.

C28 The recommended CF was derived assuming a concentration of tantalum in crustaceans of 0.027 mg/kg dry weight [55].

C29 Bowen [55] reports a concentration of tungsten of 0.5 μg/kg dry weight and Eisler [167] reports a value of <0.3 μg/kg dry weight. The recommended CF was derived assuming a concentration of tungsten in crustaceans of 0.1 μg/kg wet weight.

C30 A large number of mercury data are available, many from contaminated environments [167]. The recommended CF was derived assuming a concentration of mercury in crustaceans of 0.1 mg/kg wet weight.

C31 The recommended CF was based on whole body concentrations of ^{210}Po [203] and data from Swift and Kershaw [197].

C32 CFs for $^{239/240}Pu$ reported in the literature range from 4×10^1 to 3×10^2 for the edible fractions of crustaceans [172]. Data from Swift and Kershaw [197] were used to derive the recommended value.

C33 There is some evidence to suggest that ^{241}Am may be slightly more biologically available than plutonium [199]. The CF for americium was assumed to be the same as that for californium.

C34 The same CF as that for americium is recommended because it was assumed that the behaviour of curium and berkelium is similar to americium.

C35 The recommended CF was derived using data from Swift and Kershaw [197] and Fowler et al. [204].

TABLE V. CONCENTRATION FACTORS FOR MOLLUSCS (EXCEPT CEPHALOPODS)

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
H	1×10^0	1×10^0	See Section 3.3
C	5×10^4	2×10^4	See Section 3.3.1
Na	2×10^{-1}	3×10^{-1}	M1
S	1×10^0	3×10^0	M2
Cl	1×10^0	5×10^{-2}	M3
Ca	1×10^0	3×10^0	M4
Sc	—	1×10^5	M5
Cr	5×10^2	2×10^3	M6
Mn	1×10^4	5×10^4	M7
Fe	1×10^3	5×10^5	M8
Co	1×10^3	2×10^4	M9
Ni	1×10^2	2×10^3	M10
Zn	1×10^5	8×10^4	M11
Se	1×10^3	9×10^3	M12
Kr	—	(1×10^0)	See Section 3.3
Sr	1×10^1	1×10^1	M13
Y	1×10^3	1×10^3	M14
Zr	1×10^3	5×10^3	M15
Nb	1×10^3	1×10^3	M16
Tc	1×10^3	5×10^2	M17
Ru	2×10^3	5×10^2	M18
Pd	(3×10^2)	(3×10^2)	M14
Ag	1×10^5	6×10^4	M19
Cd	—	8×10^4	M20
In	—	(1×10^4)	M21
Sn	1×10^2	5×10^5	M22
Sb	1×10^2	3×10^2	M23
Te	1×10^3	1×10^3	M14
I	1×10^2	1×10^1	M24
Xe	—	1×10^0	See Section 3.3
Cs	1×10^1	6×10^1	M25
Ba	—	1×10^1	M26
Ce	1×10^3	2×10^3	M13
Pm	1×10^3	(7×10^3)	M27
Sm	(1×10^3)	(7×10^3)	M27
Eu	1×10^3	7×10^3	M28
Gd	—	(7×10^3)	M27
Tb	—	3×10^3	M28

TABLE V. (cont.)

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
Dy	—	(7×10^3)	M27
Tm	—	(7×10^3)	M27
Yb	—	3×10^3	M28
Hf	—	(7×10^3)	M27
Ta	—	(7×10^3)	M27
W	—	6×10^2	M29
Ir	—	(1×10^2)	M21
Hg	—	2×10^3	M30
Tl	—	6×10^3	M31
Pb	1×10^2	5×10^4	M32
Po	2×10^4	2×10^4	M7
Ra	1×10^2	1×10^2	M33
Ac	1×10^3	1×10^3	M14
Th	1×10^3	1×10^3	M33
Pa	1×10^1	5×10^2	M34
U	1×10^1	3×10^1	M35
Np	(1×10^3)	4×10^2	M36
Pu	1×10^3	3×10^3	M23
Am	2×10^3	1×10^3	M13
Cm	(2×10^3)	1×10^3	M13
Bk	—	(1×10^3)	M37
Cf	(2×10^3)	(1×10^3)	M37

[a] Values in parentheses are best estimates: see Section 3.3.

NOTES TO TABLE V

M1 The recommended CF was derived assuming a concentration of sodium in molluscs of 16 g/kg dry weight [55].

M2 The recommended CF was derived assuming a concentration of sulphur in molluscs of 16 g/kg dry weight [55].

M3 The recommended CF was derived assuming a concentration of chlorine in molluscs of 5 g/kg dry weight [55].

M4 Concentrations of calcium in molluscs reported in the literature range from 1 to 11 g/kg dry weight [55]. The recommended CF was derived assuming a concentration of calcium in molluscs of 6 g/kg dry weight.

M5 The only concentrations of scandium in molluscs available in the literature are those reported by Eisler [167] for the soft parts of mussels. The recommended CF was derived assuming the average concentration of 0.3 mg/kg dry weight.

M6 The recommended CF was derived using a mean concentration of chromium in mussels of 2 mg/kg dry weight, obtained using data from Turgeon and O'Connor [205].

M7 The recommended CF is the mean value reported by Swift and Kershaw [197].

M8 Concentrations of iron in molluscs vary considerably between and within species [167]. Interspecies differences of some magnitude clearly exist, however, and data obtained by the same author range over two orders of magnitude. Concentrations for total soft parts reported by Segar et al. [206], for example, vary from 65 to 5400 mg/kg dry weight. The geometric mean is 240 mg/kg dry weight, a value which is not inconsistent with the average of the lower end of the range of values listed by Eisler [167]. The recommended CF was derived from data from the IPSN [43], although values 100 times lower or higher have been observed [197].

M9 The recommended CF was derived using a mean concentration of cobalt in molluscs of 0.25 mg/kg wet weight from stable element data for organisms taken in 'clean' environments. However, a summary of in situ ^{60}Co data indicates CFs greater than 1×10^4 [172].

M10 The recommended CF was derived using a mean concentration of nickel in mussels of 3.1 mg/kg dry weight, obtained using data from Turgeon and O'Connor [205].

M11 Zinc is another element for which there is evident species specificity; oysters, in particular, and some gastropods, exhibit very high concentrations of zinc. Turgeon and O'Connor [205] report a mean zinc concentration of 120 mg/kg dry weight in mussels. This concentration was used to derive the recommended CF.

M12 The recommended CF was derived using a mean concentration of selenium in mussels of 1.9 mg/kg dry weight, obtained using data from Turgeon and O'Connor [205].

M13 The recommended CF was derived using data for the English Channel from the IPSN [43].

M14 No new data are available. The CF given in IAEA-TECDOC-211 [179] is therefore recommended.

M15 A range of 0.6 to 43 mg/kg dry weight for zirconium in *Mytilus edulis* is reported in the literature [207]. This gives a range of CFs between 2×10^4 and 1×10^6. However, in situ ^{95}Zr CF data [186] generally indicate values of 1×10^3 or less. Therefore, a CF of 5×10^3 is recommended.

M16 Total soft parts of *Mytilus edulis* were reported to contain <0.001 mg/kg dry weight of niobium [208]; this would give a maximum CF of 4×10^1. Both in situ and experimental data indicate CFs much greater than this, however, as summarized by Ancellin et al. [196], and thus the CF of 1 × 10^3 given in IAEA-TECDOC-211 [179] was retained.

M17 The recommended CF was derived using data from Brown et al. [200] and from the IPSN [43].

M18 A mean CF of 4 × 10^2 is reported by Swift and Kershaw [197], similar to the CF of 6 × 10^2 reported by the IPSN [43]. A CF of 5 × 10^2 for ruthenium in molluscs is therefore recommended.

M19 The recommended CF was derived using a mean concentration of silver in mussels of 0.32 mg/kg dry weight, obtained using data from Turgeon and O'Connor [205]. Oysters can display 10 times higher concentrations of silver, and therefore it is recommended that a CF 10 times higher than the CF given in Table V be used for oysters.

M20 The recommended CF was derived using a mean concentration of cadmium in mussels of 3.6 mg/kg dry weight, obtained using data from Turgeon and O'Connor [205].

M21 No new data are available.

M22 From the limited data available [167, 171] a tin concentration of 0.5 mg/kg wet weight was derived.

M23 The recommended CF was derived using data for the English Channel from the IPSN [43], consistent with data compiled by Swift and Kershaw [197].

M24 The recommended CF was derived assuming a concentration of iodine in molluscs of 4 mg/kg dry weight [55].

M25 The recommended CF was derived from in situ ^{137}Cs data in Arctic waters reported by Fisher et al. [166]. The value is consistent with data for the English Channel reported by the IPSN [43].

M26 A value of 3 mg/kg dry weight for barium is given by Bowen [55]; Karbe et al. [207] report a range of values from 0.8 to 26 mg/kg dry weight. The recommended CF was derived assuming a concentration of barium in molluscs of 0.6 mg/kg wet weight.

M27 The behaviour of these elements was assumed to be similar to that of europium, terbium and ytterbium. The recommended CF is assumed equal to the highest measured CF for the other rare earth elements (see Note M31).

M28 The recommended CFs were derived using data from Suzuki et al. [188]. Other europium data are available [207], but these have a large range and simultaneous water analyses were not made.

M29 The recommended CF was derived using a mean concentration of tungsten in mussels of 6 μg/kg wet weight, obtained using the data from Fukai and Meinke [209, 210] for soft parts of *Tapes japonicus*.

M30 The recommended CF was derived using a mean concentration of mercury in mussels of 0.13 mg/kg dry weight, obtained using data from Turgeon and O'Connor [205].

M31 The recommended CF was derived assuming a concentration of thallium in molluscs of 0.34 mg/kg dry weight [55].

M32 The recommended CF was derived using a mean concentration of lead in mussels of 8.8 mg/kg dry weight, obtained using data from Turgeon and O'Connor [205].

M33 No CF data for lamellibranch or gastropods molluscs were located.

M34 No environmental data were located. Lucu et al. [211] obtained CFs of up to 2×10^2 for the digestive tract of *Mytillus galloprovincialis* for ^{233}Pa in laboratory studies. Other tissue CFs were 60 for gill, 15 for gonad and 10 for muscle. These experiments were only of 20 days duration, and only labelled water was used. It is suggested that these values be increased by at least an order of magnitude, and therefore a CF of 5×10^2 is recommended.

M35 Reported data give ^{238}U concentrations of 3.0, 5.5, 4.6 and 13 Bq/kg dry weight for four different lamellibranch molluscs, giving a mean concentration of 1.2 Bq/kg wet weight [212]. The recommended CF was derived using this concentration and is consistent with the mean CF reported by Swift and Kershaw [197].

M36 The only published environmentally derived CFs for ^{237}Np are those given in Pentreath et al. [102]. The recommended CF is the mean of the CFs reported.

M37 The same CF as that for americium is recommended because it was assumed that the behaviour of berkelium and californium is similar to americium.

TABLE VI. CONCENTRATION FACTORS FOR MACROALGAE

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
H	1×10^0	1×10^0	See Section 3.3
C	4×10^3	1×10^4	See Section 3.3.1
Na	1×10^0	5×10^{-1}	A1
S	1×10^0	3×10^0	A2
Cl	1×10^0	5×10^{-2}	A3
Ca	1×10^0	6×10^0	A4
Sc	—	9×10^4	A5
Cr	(3×10^4)	6×10^3	A6
Mn	1×10^4	6×10^3	A7
Fe	1×10^4	2×10^4	A7
Co	1×10^3	6×10^3	A7
Ni	5×10^2	2×10^3	A8
Zn	1×10^3	2×10^3	A7
Se	1×10^3	1×10^3	A9
Kr	—	(1×10^0)	See Section 3.3
Sr	1×10^1	1×10^1	A10
Y	1×10^3	1×10^3	A11
Zr	5×10^2	3×10^3	A12
Nb	5×10^2	3×10^3	A13
Tc	1×10^5	3×10^4	A14
Ru	2×10^3	2×10^3	A15
Pd	(1×10^3)	(1×10^3)	A12
Ag	1×10^3	5×10^3	A7
Cd	—	2×10^4	A16
In	—	(5×10^3)	A17
Sn	1×10^2	2×10^5	A18
Sb	1×10^2	2×10^1	A7
Te	1×10^4	1×10^4	A11
I	1×10^3	1×10^4	A7
Xe	—	(1×10^0)	See Section 3.3
Cs	1×10^1	5×10^1	A19
Ba	—	7×10^1	A20
Ce	1×10^3	5×10^3	A21
Pm	1×10^3	(3×10^3)	A22
Sm	(1×10^3)	(3×10^3)	A22
Eu	1×10^3	3×10^3	A23
Gd	—	(3×10^3)	A22
Tb	—	2×10^3	A23
Dy	—	(3×10^3)	A22

TABLE VI. (cont.)

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
Tm	—	(3×10^3)	A22
Yb	—	8×10^2	A23
Hf	—	(3×10^3)	A22
Ta	—	(3×10^3)	A22
W	—	6×10^2	A24
Ir	—	(1×10^3)	A17
Hg	—	2×10^4	A25
Tl	—	(1×10^3)	A17
Pb	1×10^3	1×10^3	A11
Po	1×10^3	1×10^3	A11
Ra	1×10^2	1×10^2	A11
Ac	1×10^3	1×10^3	A11
Th	1×10^3	2×10^2	A26
Pa	1×10^2	1×10^2	A11
U	1×10^1	1×10^2	A27
Np	(1×10^3)	5×10^1	A28
Pu	1×10^3	4×10^3	A7
Am	2×10^3	8×10^3	A29
Cm	(2×10^3)	5×10^3	A7
Bk	—	(8×10^3)	A30
Cf	(2×10^3)	(8×10^3)	A30

[a] Values in parentheses are best estimates: see Section 3.3.

NOTES TO TABLE VI

A1 The recommended CF was derived assuming a concentration of sodium in macroalgae of 33 g/kg dry weight [55].

A2 Bowen [55] reports a mean concentration of sulphur of 9.8 g/kg dry weight for five green algae and a range of 14 to 30 g/kg dry weight for red algae; no data are given for brown algae. The recommended CF was derived using an average concentration of 16 g/kg dry weight.

A3 The only concentration of chlorine in macroalgae given by Bowen [55] is that of Vinogradov [173] for brown algae: 4.7 g/kg dry weight. This concentration was used to derive the recommended CF.

A4 From the range of calcium concentrations dry weight reported by Bowen [55], for green, red and brown algae, an average concentration of 13 g/kg dry weight was obtained. This concentration was used to derive the recommended CF.

A5 Concentrations of scandium of 0.45 and 0.07 mg/kg dry weight for red and brown algae, respectively, are reported by Horowitz et al. [213] and cited by Bowen [55]. The recommended CF was calculated assuming a mean value of 0.26 mg/kg dry weight.

A6 A wide range of chromium concentration values is indicated in the literature [55, 167]. From these data a value of 2.7 mg/kg dry weight was derived for brown algae, and means of the ranges, 7 mg/kg and 7.5 mg/kg, both dry weight, were obtained for green and red algae, respectively. An average value of 5.7 mg/kg dry weight was used to derive the recommended CF.

A7 The recommended CF was derived using data for the English Channel from the IPSN [43].

A8 A mean nickel concentration of 0.7 mg/kg wet weight was derived for red, green and brown algae from Eisler [167]. The recommended CF derived is not dissimilar from those summarized by Ancellin et al. [196] for red and brown algae and consistent with data for the English Channel from the IPSN [43].

A9 The limited data in the literature [55, 167, 171] indicate a selenium concentration in algae of about 0.05 mg/kg wet weight. This concentration was used to derive the recommended CF.

A10 Concentrations of strontium differ between the three groups of benthic algae, it being particularly accumulated by calcareous red forms such as *Halimeda.* The calcareous red algae are not of importance as far as human consumption is concerned, however, and thus such high values have not been included in the assessment. The data in the literature vary considerably. Early studies by Mauchline and Templeton [214], quoted by Eisler [167], report strontium concentrations of 6.4, 0.22 and 1.2 mg/kg wet weight for red, green and brown algae, respectively. The data in Bowen [55] indicate mid-range values of 270, 140 and 1200 mg/kg dry weight for red, green and brown algae, respectively. The recommended CF was derived using a mean concentration of about 100 mg/kg wet weight.

A11 No new data are available. The CF given in IAEA-TECDOC-211 [179] is therefore recommended.

A12 There are a number of in situ data on CFs for ^{95}Zr and ^{95}Nb. Of 12 species listed by Pentreath [215], the highest values were for green algae, which ranged from 2×10^3 to 5×10^3, while CFs for red algae were 1×10^3 or less and the maximum brown alga CF was 8×10^2. In situ data [169] also indicate a similar range. A CF of 3×10^3 is recommended.

A13 There are insufficient data to distinguish between the accumulation of ^{95}Zr and ^{95}Nb, and thus it is suggested that the zirconium data be used.

A14 The IAEA-TECDOC-211 [179] value of 1×10^5 was, presumably, based on a limited amount of data available for brown algae. It is now known that large and real differences exist in the affinities of different species for technetium. Masson et al.

[64], for example, indicate that concentrations of ^{99}Tc in red and green algae are two orders of magnitude less than those in brown algae in the vicinity of La Hague. These and other authors have also shown, experimentally, that brown algae accumulate substantially more technetium than other forms. Two independent measurements of technetium in brown algae by the IPSN in the English Channel [43] and by Brown et al. [200] determined CFs of 3×10^4, which is recommended.

A15 From the data reported by Pentreath [215], it appears that green algae accumulate more ^{106}Ru than red algae, and brown algae accumulate the least. An average CF for red and green algae of 2×10^3 can be derived, while a CF of 3×10^2 can be obtained for brown algae. These values are not inconsistent with the CFs reported by Coughtrey and Thorne [169] and Ancellin et al. [196].

A16 The recommended CF was derived using an average cadmium concentration in macroalgae of 0.15 mg/kg wet weight biased towards red and green algae. Brown algae appear to have higher concentrations, but many of the data have been derived from contaminated areas.

A17 No new data are available.

A18 The recommended CF was derived using an average concentration of tin in algae of 0.2 mg/kg wet weight from data reported by Eisler [167] and Coughtrey and Thorne [171].

A19 Data for the Irish Sea [215] indicate that CFs for ^{137}Cs vary considerably from species to species. The highest values were observed in green algae, which had a mean CF of 60. The average value for red algae was 36 and that for brown algae was 34. These data are in general agreement with the values compiled by Coughtrey and Thorne [169]. Based on these data a CF of 50 is therefore recommended.

A20 Concentrations of barium of 1.5 mg/kg dry weight in green algae, a range of 11 to 31 mg/kg dry weight in brown algae and a range of 2.8 to 50 mg/kg dry weight in red algae are cited [55]. Assuming that the larger values for red algae are those of calcareous species, the mid-range value for brown algae of 20 mg/kg dry weight was used as an average value to calculate the recommended CF. This concentration is probably too high for green algae, but possibly too low for red algae.

A21 Data in Pentreath [215] indicate much greater CFs for ^{144}Ce in green algae (average CF: 7×10^3) than in red (average CF: 2×10^3), with brown algae having the lowest values (average CF: 8×10^2). These values are somewhat higher than the data reported by Coughtrey and Thorne [169]. The stable element CFs derived by Suzuki et al. [188] are 6×10^3 for *Ulva* and a range of 5×10^2 to 3×10^3 for brown algae, which is in reasonable agreement with Pentreath [215].

A22 The behaviour of these elements was assumed to be similar to that of europium, terbium and ytterbium. The recommended CF of 3×10^3 is assumed to be equal to the highest CF of these elements.

A23 The recommended CFs are the maxima observed values for algae reported by Suzuki et al. [188].

A24 The only tungsten concentrations available in the literature are the values of 0.029 and 0.042 mg/kg dry weight in *Porphyra* and *Ulva* reported by Fukai and Meinke [210]. A concentration of 0.036 mg/kg dry weight was used to derive the recommended CF.

A25 From the data reported by Eisler [167] an average mercury concentration of 0.2 mg/kg wet weight was derived for brown algae and 0.1 mg/kg for red and green algae. The higher concentration was used to derive the recommended CF.

A26 Data in the literature [216, 217] indicate a range of CFs between 950 and 1300 for ^{230}Th and between 750 and 1300 for ^{232}Th in brown algae, on a dry weight basis. These were converted to an average wet weight CF of 2×10^2.

A27 The data reported by Holm and Persson [216] for brackish water and Nilsson et al. [217] give a dry weight CF of 700 for uranium in brown algae. Uranium-238 determinations [212], however, for *Macrocystis*, another brown alga, give an average concentration of 7.2 Bq/kg dry weight, indicating a CF of about 35. A value of 1×10^2 is recommended, but this may well be too high.

A28 The only CFs for neptunium in the literature are those reported by Pentreath et al. [102] for brown algae, which give an average CF of 30. Unpublished data, again for brown algae, indicate a range of 20 to 90. The apparent general difference in the behaviour of neptunium from that of plutonium, americium and curium has been substantiated in a number of papers [91, 199, 218].

A29 Data for ^{241}Am [102, 104, 216, 217] indicate CFs between 5×10^3 and 1×10^4 for brown algae. A mid-range CF of 8×10^3 is therefore recommended.

A30 No in situ data are available, but experimental results from Aston and Fowler [117] and Fisher et al. [218] indicate that the adsorptive behaviour of californium is similar to that of americium. The behaviour of berkelium is also assumed to be similar to that of americium.

TABLE VII. CONCENTRATION FACTORS FOR ZOOPLANKTON

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
H	1×10^0	1×10^0	See Section 3.3
C	3×10^3	2×10^4	See Section 3.3.1
Na	1×10^0	1×10^0	Z1
S	1×10^0	1×10^0	Z2
Cl	1×10^0	1×10^0	Z3
Ca	1×10^1	1×10^1	Z4
Sc	—	3×10^3	Z5
Cr	(3×10^3)	1×10^3	Z6
Mn	1×10^3	7×10^3	Z7
Fe	1×10^4	7×10^5	Z8
Co	1×10^3	7×10^3	Z9
Ni	1×10^3	1×10^3	Z10
Zn	1×10^4	1×10^5	Z9
Se	1×10^4	6×10^3	Z11
Kr	—	(1×10^0)	See Section 3.3
Sr	1×10^1	2×10^0	Z12
Y	1×10^2	1×10^2	Z13
Zr	(1×10^4)	2×10^4	Z3
Nb	(1×10^3)	(2×10^4)	Z14
Tc	1×10^3	1×10^2	Z15
Ru	(1×10^3)	3×10^4	Z3
Pd	(1×10^3)	(1×10^3)	Z13
Ag	1×10^3	2×10^4	Z9
Cd	—	6×10^4	Z9
In	—	(1×10^4)	Z16
Sn	1×10^3	5×10^5	Z17
Sb	1×10^3	8×10^1	Z18
Te	1×10^3	1×10^3	Z13
I	1×10^3	3×10^3	Z3
Xe	—	(1×10^0)	See Section 3.3
Cs	1×10^2	4×10^1	Z19
Ba	—	8×10^1	Z20
Ce	1×10^3	6×10^3	Z21
Pm	1×10^3	(4×10^3)	Z22
Sm	(3×10^3)	(4×10^3)	Z22
Eu	1×10^4	4×10^3	Z23
Gd	—	(4×10^3)	Z22
Tb	—	(4×10^3)	Z22
Dy	—	(4×10^3)	Z22

TABLE VII. (cont.)

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
Tm	—	(4×10^3)	Z22
Yb	—	(4×10^3)	Z22
Hf	—	(4×10^3)	Z22
Ta	—	(4×10^3)	Z22
W	—	(1×10^3)	Z16
Ir	—	(1×10^3)	Z16
Hg	—	4×10^3	Z24
Tl	—	(1×10^3)	Z16
Pb	1×10^4	1×10^3	Z25
Po	1×10^4	3×10^4	Z25
Ra	1×10^2	1×10^2	Z25
Ac	1×10^4	1×10^4	Z13
Th	1×10^4	1×10^4	Z25
Pa	1×10^3	1×10^3	Z13
U	5×10^0	3×10^1	Z26
Np	(2×10^3)	(4×10^2)	Z27
Pu	(2×10^3)	4×10^3	Z28
Am	(2×10^3)	4×10^3	Z29
Cm	(2×10^3)	(4×10^3)	Z30
Bk	—	(4×10^3)	Z31
Cf	(2×10^3)	(4×10^3)	Z31

[a] Values in parentheses are best estimates: see Section 3.3.

NOTES TO TABLE VII

Z1 The recommended CF was derived assuming a sodium concentration in zooplankton of 80 g/kg dry weight [55].

Z2 The CF for zooplankton is assumed to be the same CF as that for crustaceans.

Z3 The recommended CF was derived using data from Lowman et al. [219].

Z4 The recommended CF was derived assuming a calcium concentration in zooplankton of 30 g/kg dry weight [55].

Z5 The recommended CF was derived assuming a scandium concentration for whole euphausiids (*Meganyctiphanes norvegica*) of 9 µg/kg dry weight [202].

Z6 A chromium concentration for whole euphausiids of 0.85 mg/kg dry weight has been reported by Fowler [202], which is within the range of concentrations for copepods and euphausiids quoted by Eisler [167]. The recommended CF was derived using an average concentration of 0.2 mg/kg wet weight.

Z7 The recommended CF was derived using an average whole body manganese concentration for copepods and euphausiids of 4 mg/kg dry weight [167, 202].

Z8 The recommended CF was derived using an average whole body iron concentration for euphausiids of 80 mg/kg dry weight [167].

Z9 The recommended CF was derived using data from Fisher et al. [127].

Z10 The recommended CF was derived assuming a nickel concentration in zooplankton as a whole of 0.4 mg/kg wet weight.

Z11 The recommended CF was derived using an average selenium concentration for copepods of 1.3 mg/kg dry weight [127].

Z12 The recommended CF was derived using an average strontium concentration of 100 mg/kg dry weight in planktonic crustaceans in general.

Z13 No new data are available. The CF given in IAEA-TECDOC-211 [179] is therefore recommended.

Z14 The CF for niobium is assumed to be the same as that for zirconium.

Z15 Experimental data from Fowler et al. [220] gave a CF of 1×10^1; this has been increased by a factor of 10.

Z16 No new data are available.

Z17 A range of tin concentrations in zooplankton of <0.2 to 25 mg/kg dry weight is reported by Bowen [55]. Three ash weight concentrations are given in the compilation by Eisler [167]: <1.0, 50 and 70 mg/kg. On the basis of the latter values, a wet weight concentration of 0.5 mg/kg was used to derive the recommended CF, which is substantially greater than the value of 450 given by Lowman et al. [219].

Z18 The concentrations of antimony in zooplanktonic organisms given by Eisler [167] vary from 1.9 mg/kg ash to 0.037 mg/kg dry weight. A dry weight concentration of 0.07 mg/kg for a euphausiid obtained by Fowler [202] is halfway between the other two values. This value was used to derive the recommended CF, which is substantially lower than that obtained for larger crustaceans.

Z19 Yamamoto et al. [221] derived a CF of about 20 for caesium in zooplankton. Fowler [202] obtained a caesium concentration of 0.062 mg/kg dry weight for a euphausiid, which gives a CF of 40. Ballestra and Noshkin [222] report a CF of 15 for microzooplankton, and Marzano and Triulzi [223] report a value of 100. A mean value of 4×10^1 is therefore recommended.

Z20 The recommended CF was derived assuming a barium concentration in zooplankton of 25 mg/kg dry weight [55].

Z21 The cerium concentration for a euphausiid of 0.21 mg/kg dry weight given by Fowler [202] was used to derive the recommended CF, which is greater than the CF of 1×10^3 given by Lowman et al. [219].

Z22 Assuming a CF similar to that of europium.

Z23 The recommended CF was derived using the europium concentration in a euphausiid of 2.3 μg/kg dry weight reported by Fowler [202].

Z24 Bowen [55] quotes a mercury concentration of 0.11 mg/kg dry weight for zooplankton. The data given by Eisler [167] and Fowler [202] give a mean concentration of 0.22 mg/kg dry weight, which was used to derive the recommended CF.

Z25 The recommended CF was derived from the tabulations of Jackson et al. [172], excluding the lower CF data of Kharkar et al. [224].

Z26 The recommended CF was derived using data from Ballestra and Noshkin [222].

Z27 Environmental CF data for neptunium in zooplankton are scarce. Laboratory experiments [91], however, indicate that euphausiids do not accumulate ^{237}Np from sea water to the extent to which plutonium and americium are accumulated over a comparable period of time. The difference was about an order of magnitude less than plutonium and thus a CF one order of magnitude lower than the value for plutonium is recommended.

Z28 Whole euphausiid versus seawater concentrations result in a CF of 100 [225]. Data from a study of zooplankton (mainly copepods) in the Pacific Ocean indicate a CF of 1×10^4 [105]. This value is somewhat higher than the values on a volume basis quoted by Fisher and Fowler [226], which indicate CFs greater than 1×10^4 for copepods. Given a CF of 4×10^3 obtained from a single collection of microplankton from the North Pacific [222] and the same mean CF from a seasonal study in the North Pacific [227], a CF of 4×10^3 is recommended.

Z29 Fisher et al. [228] give a CF estimation of 700 for euphausiids in the Mediterranean. The data in Fowler et al. [105] for copepods in the Pacific Ocean result in a ^{241}Am CF of 6×10^3, while a separate seasonal study in the North Pacific [227] gives an average CF of 2×10^3. Since the best comparison can be made with data for the same microzooplankton (copepods) collected in the Pacific Ocean, a CF of 4×10^3 is recommended.

Z30 Environmental data for the CFs for curium are scarce in the literature. A CF similar to that of americium is therefore recommended, which is consistent with unpublished estimates of CFs greater than 1×10^3 for mixed zooplankton from the Irish Sea.

Z31 No environmental data exist on either berkelium or californium in zooplankton, but laboratory experiments [117] with ^{252}Cf resulted in CFs of 3×10^2 after eight days for uptake from water. The results indicated a rate of uptake similar to that of americium, and thus the CF for americium is recommended for both berkelium and californium.

TABLE VIII. CONCENTRATION FACTORS FOR PHYTOPLANKTON

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
H	1×10^{0}	1×10^{0}	See Section 3.3
C	3×10^{3}	9×10^{3}	See Section 3.3.1
Na	1×10^{0}	1×10^{-1}	P1
S	1×10^{0}	9×10^{-1}	P2
Cl	1×10^{0}	1×10^{0}	P3
Ca	1×10^{1}	3×10^{0}	P4
Sc	—	2×10^{3}	P3
Cr	(3×10^{3})	5×10^{3}	P5
Mn	1×10^{3}	5×10^{4}	P6
Fe	1×10^{4}	4×10^{5}	P7
Co	1×10^{3}	2×10^{3}	P8
Ni	1×10^{3}	3×10^{3}	P9
Zn	1×10^{4}	1×10^{4}	P10
Se	1×10^{4}	3×10^{4}	P11
Kr	—	(1×10^{0})	See Section 3.3
Sr	1×10^{1}	1×10^{0}	P12
Y	1×10^{2}	1×10^{2}	P13
Zr	(1×10^{4})	6×10^{4}	P3
Nb	(1×10^{3})	1×10^{3}	P3
Tc	1×10^{3}	4×10^{0}	P14
Ru	(1×10^{3})	2×10^{5}	P3
Pd	(1×10^{3})	(1×10^{3})	P13
Ag	1×10^{3}	5×10^{4}	P15
Cd	—	1×10^{3}	P16
In	—	(1×10^{3})	P17
Sn	1×10^{3}	7×10^{4}	P16
Sb	1×10^{3}	1×10^{3}	P13
Te	1×10^{3}	1×10^{3}	P13
I	1×10^{3}	8×10^{2}	P18
Xe	—	(1×10^{0})	See Section 3.3
Cs	1×10^{2}	2×10^{1}	P19
Ba	—	8×10^{2}	P10
Ce	1×10^{3}	9×10^{4}	P3
Pm	1×10^{3}	(9×10^{4})	P20
Sm	(3×10^{3})	(9×10^{4})	P20
Eu	1×10^{4}	(9×10^{4})	P20
Gd	—	(9×10^{4})	P20
Tb	—	(9×10^{4})	P20
Dy	—	(9×10^{4})	P20

TABLE VIII. (cont.)

Element	IAEA-TECDOC-211 value[a] [179]	Recommended value[a]	Note
Tm	—	(9×10^4)	P20
Yb	—	(9×10^4)	P20
Hf	—	(9×10^4)	P20
Ta	—	(9×10^4)	P20
W	—	(9×10^4)	P20
Ir	—	(9×10^4)	P20
Hg	—	1×10^5	P10
Tl	—	(1×10^3)	P17
Pb	1×10^4	1×10^5	P10
Po	1×10^4	7×10^4	P21
Ra	1×10^2	2×10^3	P22
Ac	1×10^4	1×10^4	P13
Th	1×10^4	4×10^5	P10
Pa	1×10^3	1×10^3	P13
U	5×10^0	2×10^1	P23
Np	(2×10^3)	1×10^2	P24
Pu	(2×10^3)	2×10^5	P24
Am	(2×10^3)	2×10^5	P24
Cm	(2×10^3)	2×10^5	P25
Bk	—	(2×10^5)	P26
Cf	(2×10^3)	2×10^5	P24

[a] Values in parentheses are best estimates: see Section 3.3.

NOTES TO TABLE VIII

P1 The recommended CF was derived assuming a sodium concentration in phytoplankton of 6 g/kg dry weight [55].

P2 Bowen reports a concentration range of 3 to 6 g/kg dry weight [55]. An average value of 4.5 g/kg dry weight was used to derive the recommended CF.

P3 The recommended CF was derived using data from Lowman et al. [219].

P4 The recommended CF was derived assuming a calcium concentration in phytoplankton of 6.1 g/kg dry weight [55].

P5 A range of chromium concentrations in phytoplankton of 2.2 to 7.5 mg/kg dry weight is given by Bowen [55]. A mean value of 5 mg/kg dry weight was used to derive the recommended CF.

P6 A very large range of manganese concentrations in phytoplankton of 4 to 120 mg/kg dry weight is given by Bowen [55]. Average dry weight concentrations of 22 and 35 mg/kg were obtained from Eisler [167]. The recommended CF was derived using a mean value of 29 mg/kg dry weight from the latter.

P7 Sunda and Hunstman [229] report a range of iron/carbon values in algal cells. An appropriate value would be 10 µmol Fe/mol C, which can be converted to approximately 70 nmol Fe/g wet weight. Assuming a surface iron concentration of 200 pM [48], a wet weight CF, equivalent to a vol./vol. CF, of 3.5×10^5 was derived, which was rounded to 4×10^5.

P8 The recommended CF is the average of the CFs for two phytoplankton species given by Fisher and Reinfelder [230]. Lowman et al. [209] report a value of about 1×10^3.

P9 Martin and Knauer [231] give a range of nickel concentrations in phytoplankton of 1.9 to 7.8 mg/kg dry weight, while Laevastu and Thompson [232] report a concentration of 5.5 mg/kg dry weight, and a concentration of 1.5 mg/kg wet weight can be derived for whole diatoms from the data in Eisler [167]. An average value of 1 mg/kg wet weight was used to derive the recommended CF.

P10 The recommended CF is the geometric mean value of the CFs for five phytoplankton species given by Fisher and Reinfelder [230].

P11 Baines and Fisher [233] show that CFs for selenite vary greatly among taxonomic groups, with values ranging from 7×10^1 to 2×10^5. The recommended CF is the mean CF for 14 species.

P12 The recommended CF was derived using an average concentration of 60 mg/kg wet weight, obtained from data reported by Eisler [167].

P13 No new data are available. The CF given in IAEA-TECDOC-211 [179] is therefore recommended.

P14 The recommended CF was derived using data from Fisher [234].

P15 The recommended CF is the geometric mean value of the CFs for six phytoplankton species given by Fisher and Reinfelder [230].

P16 The recommended CF is the geometric mean value of the CFs for four phytoplankton species given by Fisher and Reinfelder [230].

P17 No new data are available.

P18 The recommended CF was derived using a mean iodine concentration in phytoplankton of 270 mg/kg dry weight given by Bowen [55].

P19 The recommended CF is the mean CF of 2×10^1 (range: 1×10^1–1×10^2) given for five species of phytoplankton by Heldal et al. [235].

P20 No direct measurements are available; CFs for these elements in phytoplankton are assumed to be equal to that of cerium.

P21 The recommended CF is the average of the CFs for two phytoplankton species given by Fisher and Reinfelder [230].

P22 The recommended CF was derived using data from Jackson et al. [172].

P23 The recommended CF was derived using data from Szefer and Ostrowski [236].

P24 The recommended CF was derived using data from Fisher et al. [218].

P25 The recommended CF was derived using data from Fisher and Fowler [226].

P26 The behaviour of berkelium is assumed to be similar to that of curium, and therefore the recommended CF is the same as that for curium.

TABLE IX. CONCENTRATION FACTORS FOR CEPHALOPODS

Element	Recommended value	Note
Sc	2×10^2	CE1
Cr	5×10^3	CE2
Mn	3×10^3	CE3
Fe	1×10^5	CE4
Co	3×10^2	CE5
Ni	1×10^3	CE6
Zn	6×10^4	CE7
Sr	2×10^0	CE8
Zr	5×10^1	CE9
Ru	5×10^1	CE8
Cd	1×10^4	CE10
Sb	2×10^1	CE11
Cs	9×10^0	CE12
Ce	3×10^1	CE8
Hg	1×10^4	CE13
Pb	7×10^2	CE14
Po	2×10^4	CE15
Th	6×10^4	CE16
Pu	5×10^1	CE17
Am	1×10^2	CE18

NOTES TO TABLE IX

CE1 The recommended CF was derived using the scandium concentration for whole squid of 0.01 mg/kg ash (0.1 μg/kg wet weight) given by Eisler [167].

CE2 The recommended CF was derived using the chromium concentration in squid flesh with skin of 4.7 mg/kg dry weight reported by Eisler [167].

CE3 Several data are available for manganese. Eustace [237] gives a concentration of 0.6 mg/kg wet weight for whole octopus; Ishii et al. [238] report a concentration of 1.4 mg/kg dry weight for the trunk of *Sepia*; Horowitz and Presley [239] give a value of 1.8 mg/kg dry weight for flesh with skin of squid — all quoted by Eisler [167]. Nakahara et al. [178] give an average concentration of 0.14 mg/kg wet weight for muscle of a number of cephalopods. The recommended CF was derived assuming a mean concentration of 0.3 mg/kg wet weight (excluding the whole octopus value).

CE4 Of the iron data considered, Ishii et al. [238] give a trunk concentration of 16 mg/kg dry weight for *Sepia*; Matsumoto et al. [240] report a value of 8 mg/kg wet weight for whole *Sepia*; Horowitz and Presley [239] give a concentration of

19.3 mg/kg dry weight for flesh with skin of squid, and Nakahara et al. [178] an average value of 1.8 mg/kg wet weight for several species. The recommended CF was derived assuming a concentration of 3 mg/kg wet weight.

CE5 The cobalt concentration of 0.06 mg/kg dry weight for the trunk of *Sepia* given by Ishii et al. [238] is greater than any values reported by Nakahara et al. [178] for the muscle of several cephalopods (average concentration: 5.3 µg/kg wet weight; range: 2.2–8.8 µg/kg wet weight). The recommended CF was derived assuming a concentration of 5 µg/kg wet weight.

CE6 Two nickel concentrations are available: 1.1 mg/kg dry weight for *Sepia* trunk given by Ishii et al. [238] and 2.5 mg/kg dry weight for squid flesh with skin reported by Horowitz and Presley [239]. A value of 0.35 mg/kg wet weight was used to derive the recommended CF.

CE7 A number of zinc concentrations are available: 18.5 mg/kg wet weight for whole octopus [237]; 58 mg/kg dry weight for the trunk of *Sepia* [238]; 16 mg/kg wet weight for the mantle of *Sepia* [241] and 52 mg/kg dry weight for the same tissue [242]; 144 mg/kg dry weight for the flesh with skin of squid [239]; and an average of 12.2 mg/kg wet weight for muscle of a number of species [240]. The average concentration from these data, 16 mg/kg wet weight, was used to derive the recommended CF.

CE8 The recommended CF was derived using data from Kurabayashi et al. [189].

CE9 The recommended CF was derived using data for ^{95}Zr and ^{95}Nb from Kurabayashi et al. [189].

CE10 Hamanaka et al. [243] report a cadmium concentration of 0.72 mg/kg dry weight for the muscle of *Ommastrephes bartrami*, while Horowitz and Presley [239] give a value of 1 mg/kg dry weight for the flesh with skin of squid, and Leatherland and Burton [242] report a concentration of 0.03 mg/kg dry weight for the mantle of *Sepia*. A concentration of 0.1 mg/kg wet weight was used to derive the recommended CF.

CE11 The only antimony concentrations available are 0.01 mg/kg dry weight for *Sepia* mantle [242] and 0.46 mg/kg ash for whole squid [195]. The recommended CF was derived using a mean concentration of 3.5 µg/kg wet weight.

CE12 Ishii et al. [238] report a caesium concentration of 0.016 mg/kg dry weight for *Sepia* trunk, which gives a CF of 9×10^0. This is consistent with the in situ CF for ^{137}Cs of 1×10^1 obtained from the data from Kurabayashi et al. [179] and the mean CF of 1.4×10^1 from the data from Suzuki et al. [244]. A value of 1×10^1 is therefore recommended.

CE13 A number of mercury concentration data are available [167], from which a mean of 0.1 mg/kg wet weight was obtained to derive the recommended CF.

CE14 The recommended CF is the mean value for ^{210}Pb (whole animal) reported by Heyraud and Cherry [203].

CE15 Guary et al. [245] give a CF of 2×10^3 for ^{210}Po in octopus 'remainder', which is below the range for whole cephalopods given by Heyraud and Cherry [203]. The average value is 2×10^4.

CE16 The recommended CF was taken from the ^{232}Th data for octopus 'remainder' given by Guary et al. [245].

CE17 The recommended CF is the CF for cephalopods taken off Tokai, Japan, given in Kurabayashi et al. [189]. Guary et al. [245] report a CF for $^{239/240}$Pu of 6×10^1 for whole octopus.

CE18 The recommended CF is the CF for ^{241}Am for 'remainder' of octopus given by Guary et al. [245].

TABLE X. CONCENTRATION FACTORS FOR PINNIPEDS (SEALS, SEA LIONS)

Element	Muscle		Liver		Note
	Recommended value	Range	Recommended value	Range	
Cr	—	—	—	—	—
Mn	1×10^4	—	5×10^4	—	PN1
Fe	1×10^7	7×10^6–1×10^7	3×10^7	1×10^6–1×10^8	PN2
Co	1×10^3	—	2×10^3	—	PN3
Ni	—	—	—	—	—
Zn	1×10^5	6×10^4–2×10^5	2×10^5	1×10^5–3×10^5	PN4
Se	1×10^4	7×10^3–3×10^4	7×10^5	3×10^4–9×10^6	PN5
Ag	$<6 \times 10^4$	—	7×10^4	—	PN6
Cd	2×10^4	5×10^2–1×10^4	7×10^5	5×10^3–1×10^7	PN7
Cs	4×10^2	3×10^1–1×10^3	3×10^2	—	PN8
Hg	3×10^4	7×10^3–2×10^5	2×10^6	1×10^4–2×10^7	PN9
Pb	3×10^3	3×10^2–2×10^4	1×10^5	3×10^2–9×10^5	PN10
Pu	—	—	8×10^0	3×10^0–2×10^1	PN11

NOTES TO TABLE X

PN1 Values derived from data from Yeats et al. [246] using a concentration of manganese in sea water of 103 ng/L.

PN2 Values derived from data from Thompson [247] and Yeats et al. [246] using a concentration of iron in sea water of 22 ng/L.

PN3 Values derived from data from Yeats et al. [246] using a concentration of cobalt in sea water of 10 ng/L.

PN4 Values derived from data from Thompson [247] and Yeats et al. [246] using a concentration of zinc in sea water of 250 ng/L.

PN5 Values derived from data from Thompson [247] and Yeats et al. [246] using a concentration of selenium in sea water of 40 ng/L.

PN6 Values derived from data from Yeats et al. [246] using a concentration of silver in sea water of 1.0 ng/L.

PN7 Values derived from data from Thompson [247] and Yeats et al. [246] using a concentration of cadmium in sea water of 8 ng/L.

PN8 Data are compiled from Holm et al. [248], Anderson et al. [249], Calmet et al. [250] and Watson et al. [251] using a wet/dry ratio for seal muscle of 3.4 [252], where necessary. In addition, values are computed from Anderson et al. [249]

using seawater data for a corresponding period reported by Camplin [253] and Carroll et al. [254].

PN9 Values derived from data from Thompson [247] and Yeats et al. [246] using a concentration of mercury in sea water of 10 ng/L.

PN10 Values derived from data from Thompson [247] and Yeats et al. [246] using a concentration of lead in sea water of 20 ng/L.

PN11 Values derived from data from Watson et al. [251] using concentrations of plutonium in sea water for 1995 from Leonard et al. [255].

TABLE XI. CONCENTRATION FACTORS FOR POLAR BEARS

Element	Muscle		Liver		Note
	Recommended value	Range	Recommended value	Range	
Cr	—	—	—	—	—
Mn	—	—	—	—	—
Fe	—	—	—	—	—
Co	—	—	—	—	—
Ni	—	—	—	—	—
Zn	3×10^5	2×10^5–3×10^5	2×10^5	2×10^5–3×10^5	PB1
Se	8×10^3	5×10^3–1×10^4	1×10^5	3×10^4–3×10^5	PB2
Ag	—	—	—	—	—
Cd	2×10^3	$<2 \times 10^3$–6×10^3	1×10^5	2×10^4–3×10^5	PB3
Cs	1×10^2	—	—	—	PB4
Hg	9×10^3	3×10^3–2×10^4	1×10^6	2×10^5–2×10^6	PB5
Pb	—	—	—	—	—
Pu	7×10^1	—	—	—	PB6

NOTES TO TABLE XI

PB1 Values derived from data from Dietz et al. [256] using a concentration of zinc in sea water of 250 ng/L.

PB2 Values derived from data from Dietz et al. [256] using a concentration of selenium in sea water of 40 ng/L.

PB3 Values derived from data from Dietz et al. [256] using a concentration of cadmium in sea water of 8 ng/L.

PB4 Values derived from data from Holm et al. [256] using a concentration of caesium in sea water of 10 mBq/L and a muscle wet/dry ratio of 4.74 [252].

PB5 Values derived from data from Dietz et al. [256] using a concentration of mercury in sea water of 10 ng/L.

PB6 Values derived from data from Holm et al. [248] using an activity concentration of plutonium in sea water of 13 μBq/L and a muscle wet/dry ratio of 4.74 [252].

TABLE XII. CONCENTRATION FACTORS FOR CETACEANS (WHALES, DOLPHINS, PORPOISES)

Element	Muscle		Liver		Note
	Recommended value	Range	Recommended value	Range	
Cr	$<6 \times 10^3$	—	—	—	CT1
Mn	$<7 \times 10^4$	—	—	—	CT2
Fe	7×10^6	2×10^6–1×10^7	2×10^7	1×10^7–3×10^7	CT3
Co	—	—	—	—	—
Ni	$<2 \times 10^3$	—	—	—	CT4
Zn	7×10^4	3×10^4–2×10^5	2×10^5	9×10^4–4×10^5	CT5
Se	8×10^4	3×10^3–4×10^5	4×10^5	3×10^3–1×10^6	CT6
Ag	—	—	—	—	—
Cd	2×10^4	$<1 \times 10^4$–5×10^4	3×10^6	$<1 \times 10^4$–9×10^6	CT7
Cs	3×10^2	3×10^1–6×10^2	—	—	CT8
Hg	2×10^5	2×10^4–7×10^5	5×10^6	4×10^4–5×10^7	CT9
	5×10^3	1×10^3–5×10^4	1×10^4	1×10^3–4×10^4	
Pb	4×10^4	$<5 \times 10^2$–2×10^5	6×10^4	5×10^2–2×10^5	CT10
Pu	—	—	3×10^0	—	CT11

NOTES TO TABLE XII

CT1 Values derived from data from Thompson [247] using a concentration of chromium in sea water of 169 ng/L.

CT2 Values derived from data from Thompson [247] using a concentration of manganese in sea water of 103 ng/L.

CT3 Values derived from data from Thompson [247] using a concentration of iron in sea water of 22 ng/L.

CT4 Values derived from data from Thompson [247] using a concentration of nickel in sea water of 250 ng/L.

CT5 Values derived from data from Thompson [247] using a concentration of zinc in sea water of 250 ng/L.

CT6 Values derived from data from Thompson [247] using a concentration of selenium in sea water of 40 ng/L.

CT7 Values derived from data from Thompson [247] using a concentration of cadmium in sea water of 8 ng/L.

CT8 Values derived from data from Calmet et al. [250] and Sickel et al. [257] using an activity concentration of caesium in sea water of 5.5 mBq/L [166].

CT9 Values derived from data from Thompson [247] using a concentration of mercury in sea water of 10 ng/L. The lower value is for baleen whales (*Mysticeti*), which feed lower in the food chain.

CT10 Values derived from data from Thompson [247] using a concentration of lead in sea water of 20 ng/L.

CT11 Value derived from data from Watson et al. [251] using concentrations of plutonium in sea water for 1995 from Leonard et al. [255].

Appendix

CONCENTRATION FACTORS FOR DEEP OCEAN FERROMANGANESE NODULES

In the years preceding the publication of TRS 247 there had been considerable discussion on the potential of mining deep sea ferromanganese nodules as a source of trace metals. It was considered useful to include the mining of nodules as a potential whereby radionuclides disposed of in the deep ocean could have a radiological impact on the human population. At present, nodules are not being considered as a source of metals on a commercial scale. It was not thought to be justified to conduct an extensive review of the availability of new data since the publication of TRS 247. However, the values in Table XIII have been adjusted to take account of the revised deep water element concentrations. The following paragraphs are taken from TRS 247.

In addition to average pelagic sediments K_ds, CFs for deep ocean ferromanganese nodules are required for modelling purposes. These CFs have merely been derived from a comparison of the total concentrations of metals in manganese nodules with those in deep ocean water. The elements in such nodules, excluding constituents of the host nucleus around which accretion occurs, are assumed to be derived from sea water. Thus the composition of nodules is determined by authigenic processes, and it is doubtful that the reactions are wholly reversible. However, no reduction of the CFs to account for the proportion of exchangeable phase material in these matrices was felt justified for the intended application. The compilation of abundances in ferromanganese nodules [55], together with the calculated CFs, is shown in Table XIII. In the cases of promethium, hafnium and radium, for which there exist no reliable estimates of their concentrations in ferromanganese nodules, values derived by Li [58, 258] have been given.

In a situation of continuous input of a radionuclide into the water column, the stable element derived value is clearly applicable because the decay constant for the nuclide, relating to the quantity in the water and the nodule, cancels out. For purposes of calculation of the IAEA's definition of radioactive waste unsuitable for dumping at sea, which assumes continuous input, the CFs as given in Table XIII are used. Where the input is not constant, however, it can be assumed that physical decay will reduce the CF value, because this process is faster than that of nodule growth. It should also be pointed out that where input is likely to be of limited duration it may be more appropriate, for radionuclides with a half-life of less than 100 years, to assume that manganese nodules respond like any other particle, with adsorption–desorption reactions occurring at its surface; thus CFs considerably lower than those given in Table XIII would be more appropriate for deep sea sediments. The relatively large particle size of ferromanganese nodules that are likely to be exploited commercially, their very slow accretion rate and the fact that adsorption–exchange only occurs at external surfaces, could probably best be accounted for by the introduction of a modifying factor to the nodule CFs given in Table XIII for exposure pathway calculations for short lived and medium lived radionuclides. This modifying factor would correspond to the ratio of the average mass of the thin surface shell (that is likely to be involved in adsorption–exchange reactions) to the average mass of nodules being considered in the exposure pathway.

TABLE XIII. DEEP OCEAN FERROMANGANESE NODULE CONCENTRATION FACTORS

Element	Concentration in ferromanganese nodules (kg/kg) [55]	Derived CF	Value from Refs [58, 258]
Na	1.9×10^{-2}	2×10^{0}	—
S	7.5×10^{-4}	8×10^{-1}	—
Ca	2.5×10^{-2}	6×10^{1}	—
Sc	1×10^{-5}	1×10^{7}	—
Cr	1.4×10^{-5}	6×10^{4}	—
Mn	1.6×10^{-1}	6×10^{9}	—
Fe	1.6×10^{-1}	4×10^{9}	—
Co	3×10^{-3}	3×10^{9}	—
Ni	4.9×10^{-3}	1×10^{7}	—
Zn	7.1×10^{-4}	2×10^{6}	—
Sr	8.3×10^{-4}	9×10^{1}	—
Y	3.1×10^{-4}	7×10^{7}	—
Zr	6.5×10^{-4}	3×10^{7}	—
Nb	$\sim 1 \times 10^{-5}$	$\sim 2 \times 10^{6}$	—
Pd	7×10^{-10}	1×10^{4}	—
Ag	6×10^{-6}	7×10^{5}	—
Cd	8×10^{-6}	1×10^{5}	—
In	2.5×10^{-7}	3×10^{6}	—
Sn	2.7×10^{-6}	3×10^{6}	—
Sb	$\sim 1 \times 10^{-5}$	$\sim 4 \times 10^{4}$	—
Te	4.8×10^{-5}	4×10^{8}	—
I	$\sim 5 \times 10^{-4}$	$\sim 1 \times 10^{4}$	—
Cs	5×10^{-7}	2×10^{3}	—
Ba	2×10^{-3}	1×10^{5}	—
Ce	7.2×10^{-4}	2.4×10^{8}	—
Pm	—	—	5×10^{7}
Pr	5×10^{-5}	2×10^{8}	—
Sm	9×10^{-5}	8×10^{7}	—
Eu	1.4×10^{-5}	5×10^{7}	—
Gd	6.4×10^{-6}	3×10^{6}	—
Th	1×10^{-5}	4×10^{7}	—
Dy	4.2×10^{-5}	5×10^{7}	—
Tm	$<2.4 \times 10^{-6}$	$<8 \times 10^{6}$	—
Yb	6.4×10^{-6}	3×10^{6}	—
Hf	$\sim 1 \times 10^{-7}$	$\sim 5 \times 10^{5}$	3×10^{5}
W	6×10^{-5}	6×10^{5}	—
Ir	9×10^{-9}	—	—

TABLE XIII. (cont.)

Element	Concentration in ferromanganese nodules (kg/kg) [55]	Derived CF	Value from Refs [58, 258]
Hg	5×10^{-7}	2×10^{6}	—
Tl	1×10^{-4}	1×10^{7}	—
Pb	8.7×10^{-4}	2×10^{8}	—
Ra	—	—	3×10^{5}
Th	—	1×10^{8}	—
U	1×10^{-5}	3×10^{3}	—

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Consultants Meetings

Monaco: 25–28 April 2000;
Vienna, Austria: 30 October–3 November 2000, 2–4 December 2002