

# Cobalt-60 and the environment

$^{60}_{27}\text{Co}$



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This fact sheet describes the behaviour of the chemical element in the principal compartments of terrestrial and aquatic ecosystems using the following assumptions. Isotope discrimination is negligible, which is verified for most of the elements considered. When the element has stable isotopes, the behavioural analogy between the stable and radioactive isotopes is accepted implicitly, with the understanding that for naturally-occurring elements, the chemical form and emission environment for anthropogenic discharge may involve pathways and transfer processes different from those identified for the stable natural element.

The radioactive isotope designated in the title of the fact sheet has major radioecological importance with regard to quantity and persistence in the environment, with other isotopes, both radioactive and stable, being cited as well. The information, which has intentionally been simplified, is intended to reflect the state of knowledge on the topic at the time of publication and provide values for the principal radioecological parameters normally used to estimate transfer in the environment and in the food chain in particular.

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## Characteristics

### Chemical characteristics

Cobalt is a grey, lustrous, ferromagnetic metal. It does not react with water or air at ambient temperature. Cobalt salts form complexes and act as oxidising agents.

Cobalt can exist in oxidation states +II and +III in solution. The +II state ( $\text{Co}^{2+}$ ) is considered as the more stable of the two under most environmental conditions. Some organic complex-forming agents, however, can stabilise the +III state, which is usually unstable, and avoid its reduction (Krupa and Serne, 2002).

### Nuclear characteristics

Cobalt has 37 radioisotopes with mass numbers from 47 to 75. Of these,  $^{59}\text{Co}$  is the only stable isotope. The three most widely produced anthropogenic isotopes are  $^{57}\text{Co}$ ,  $^{58}\text{Co}$  and  $^{60}\text{Co}$ . Of these, only  $^{60}\text{Co}$  has a half-life of more than a year.

	$^{60}\text{Co}$
<b>Radioactive half-life</b>	5.27 years
<b>Specific activity</b>	$4.19 \times 10^{13} \text{ Bq.g}^{-1}$
<b>Precursors</b>	$^{60\text{m}}\text{Co}$ (from $^{60}\text{Fe}$ )
<b>Decay product</b>	$^{60}\text{Ni}$
<b>Principal emission through disintegration (emission probability, %)</b>	$\beta^-$ 318 keV (99.9%) $\gamma$ 1,332 keV (100%) and 1,173 keV (99.9%)

(Nucleonica, EC 2009)

## Origins

### Natural origins

Stable cobalt,  $^{59}\text{Co}$ , occurs in the Earth's crust at a concentration ranging from  $2 \mu\text{g.g}^{-1}$  in carbonate rocks to  $25 \mu\text{g.g}^{-1}$  in igneous rocks (Coughtrey and Thorne, 1983). Its principal ores are sulphide or arsenic sulphide ores (cobaltite, smaltite and linnaeite). Cobalt is used to make many alloys with applications in the electrical and aeronautical industries. It is also used in making permanent magnets, refractory metals and pigments and as an additive in agriculture (Hamilton, 1994).

Cobalt is present in ocean water at a concentration ranging from approximately  $0.5$  to  $10 \text{ ng.L}^{-1}$  (Huynh Ngoc and Whitehead, 1986; Ellwood and Van der Berg, 2001). Off the coasts of England, it occurs in North Sea surface coastal water at an approximate concentration of  $2$  to  $50 \text{ ng.L}^{-1}$  (Achterberg *et al.*, 2003). Its average concentration is  $1 \mu\text{g.L}^{-1}$  in fresh water and from  $0.4$  to  $2.0 \text{ ng.m}^{-3}$  in air (ATSDR, 2004). The chief natural sources of the stable isotope are wind erosion, sea spray, volcanic eruptions and forest fires. The radioactive isotopes are man-made.

It is an essential trace element, particularly as the nucleus of vitamin B12 (cyanocobalamin), which is a coenzyme in many enzyme reactions including those of haematopoiesis.

### Artificial origins

Cobalt-60 is a neutron activation product formed from structural materials in nuclear reactors. It can also be produced industrially through neutron activation of stable cobalt. It is used in nuclear medicine.

Radiocobalts (the radioactive isotopes of cobalt) are found in nuclear power reactors. They currently account for 39% of total gamma activity discharged as liquid effluent, with a total of  $2.7 \times 10^9 \text{ Bq}$  of  $^{58}\text{Co}$  and  $3.5 \times 10^9 \text{ Bq}$  of  $^{60}\text{Co}$  from all EDF plants in 2007. The period from 2003 to 2007 saw a 72% drop in  $^{58}\text{Co}$  discharge and a 35% drop for  $^{60}\text{Co}$  (Bresson *et al.*, 2009).

In spent fuel reprocessing facilities, cobalt comes from fuel assemblies on which activation products have bound as oxides. For the most part it is discharged with liquid effluent. Effluent activity due to  $^{60}\text{Co}$  amounted to  $8.8 \times 10^{10} \text{ Bq}$  for the La Hague plant in 2009. Since it was commissioned in 1967, this plant

has discharged  $7.2 \times 10^{12}$  Bq of  $^{60}\text{Co}$  to the sea (activity corrected for decay as of 01/01/2010). This value was  $7.2 \times 10^{10}$  Bq for the Sellafield plant in the UK in 2008. Furthermore, the Marcoule plant discharged between  $2.5$  and  $3.0 \times 10^{10}$  Bq.year $^{-1}$  of  $^{60}\text{Co}$  into the River Rhone until 1997 (Van der Stricht and Janssens, 2001). Lastly,  $^{60}\text{Co}$  is among the radionuclides found in nuclear waste.

## Environmental concentrations

The atmospheric fallout from nuclear weapons testing and the Chernobyl accident contains no  $^{60}\text{Co}$ . Consequently, this radionuclide is not responsible for any 'environmental background', unlike  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$  and the plutonium isotopes. Its presence in the environment is therefore for the most part related to nuclear facilities.

For some twenty years now, the authorised discharges of  $^{60}\text{Co}$  from these facilities to the atmosphere do not lead to activities of this radionuclide being detectable in the air or terrestrial environment, except under highly specific atmospheric conditions. For example, atmospheric activity related to gaseous discharge from AREVA's La Hague plant are currently modelled at level of around  $10^{-8}$  Bq.m $^{-3}$  of air, whereas the most effective detection limits exceed  $10^{-7}$  Bq.m $^{-3}$ . Similarly, activity levels modelled in sensitive foodstuffs, such as salad vegetables, are around  $5.0 \times 10^{-5}$  Bq.kg $^{-1}$  wet, whereas the best achievable detection limits are nearly 1,000 times higher than this ( $2.0$  to  $5.0 \times 10^{-2}$  Bq.kg $^{-1}$  wet; Renaud and Gurrarian, 2009). Lastly, gaseous discharge levels from other nuclear facilities, particularly nuclear power plants, are at least ten times lower than those from AREVA's La Hague plant.

However,  $^{60}\text{Co}$  is measured in aquatic environments affected by liquid effluent discharged from nuclear facilities.

In river environments, it is measured up to 20 km downstream of nuclear power plants in sediments ( $10^{-1}$  to a few Bq.kg $^{-1}$  dry) and plants known to be biological indicators of environmental contamination. The concentration of  $^{60}\text{Co}$  in these plants has been falling steadily since 1983 (Eyrolle, 2009) reflecting reduced radioactive discharge (Figure 1). In more than 70% of cases, it is now below the detection limit, which is usually between  $5.0 \times 10^{-2}$  and  $8.0 \times 10^{-1}$  Bq.kg $^{-1}$  wet. In the past twenty years, cobalt-60 has never been detected in the flesh of river fish, despite detection limits in the region of  $3.0 \times 10^{-2}$  to  $6.0 \times 10^{-2}$  Bq.kg $^{-1}$  wet. It should also be noted that cobalt isotopes 58 and 60, when detected in a river environment subject to the influence of nuclear power plants, exhibit similar concentration ranges, a fact that is consistent with discharged activity levels, which are also very close.

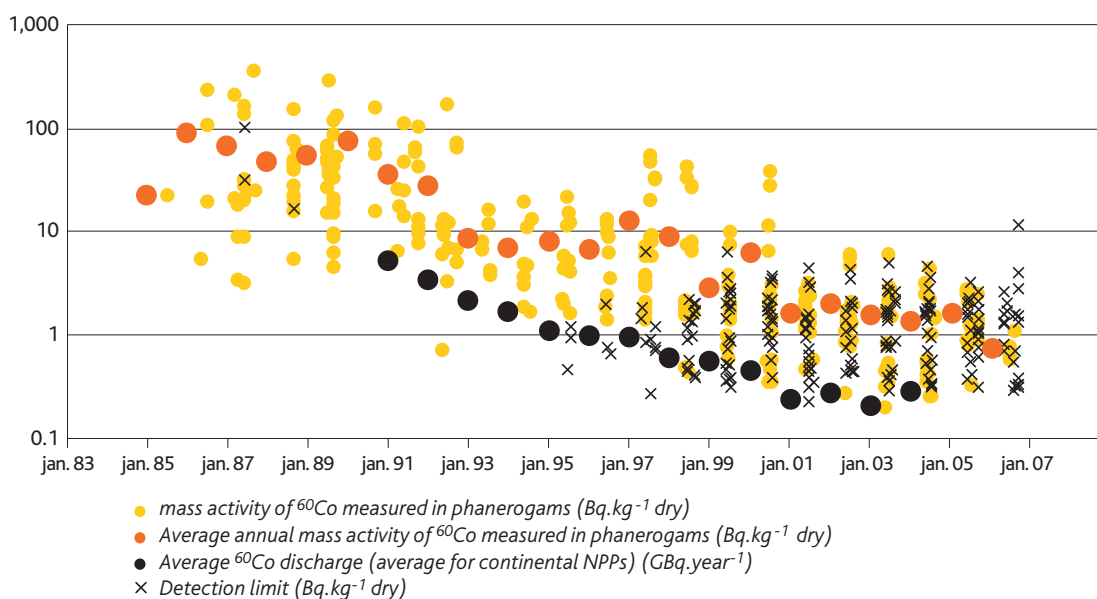


Figure 1: Changes in  $^{60}\text{Co}$  discharged in liquid effluent and its concentration in freshwater plant samples taken by IRSN downstream of NPPs (1985-2006) according to Eyrolle, 2009.

In the 1980s,  $^{60}\text{Co}$  measurements taken in the Channel within the area impacted by liquid discharge from AREVA's La Hague plant revealed an influence of these effluents, with concentrations in the water ranging from 1 to 40 mBq.L $^{-1}$  (average value of 6 mBq.L $^{-1}$ ). Levels began to drop significantly as of the 1990s and are now hard to detect. Recent measurements show concentrations in the region of 0.1 to 0.3 mBq.L $^{-1}$

in the immediate vicinity of the plant outfall. In other seawater areas,  $^{60}\text{Co}$  level is below the detection limit. The same trend can be seen in sediments, where  $^{60}\text{Co}$  concentrations varied from a few tenths to a few hundred  $\text{Bq.kg}^{-1}$  dry (Boust, 1999) or even a few thousand  $\text{Bq.kg}^{-1}$  dry in the immediate vicinity of the outfall (IPSN, 1999; Germain *et al.*, 2004). These concentrations have been dropping since they reached their peak in 1990. For example, concentration measurements taken in sediments on the North Cotentin sandy-silty foreshore dropped from  $40 \text{ Bq.kg}^{-1}$  dry in 1993 to  $1 \text{ Bq.kg}^{-1}$  dry in 2003 (Fiévet and Germain, 2004). In the Irish Sea,  $^{60}\text{Co}$  levels in sediments were less than  $2 \text{ Bq.kg}^{-1}$  dry in 2008 near the Sellafield spent fuel reprocessing plant (CEFAS, 2009).

Cobalt-60 was one of the few gamma-emitting anthropogenic radionuclides that could be detected in marine plants in 2008 (along with  $^{137}\text{Cs}$  and, in some cases,  $^{106}\text{Rh}$ ). Since 1987, concentrations have fallen by a factor of about 90 in *Fucus serratus* algae (Germain *et al.*, 1990; Fiévet and Germain, 2004). Cobalt-60 concentration levels are below the detection limit in algae along the Atlantic coast and in the western Channel and are declining east of North Cotentin. In 2009, they were below  $0.3 \text{ Bq.kg}^{-1}$  dry near the Dover Strait. Coastal nuclear power plants also discharge a little  $^{60}\text{Co}$  and  $^{58}\text{Co}$  leading to some slight environmental traces. In the Irish Sea,  $^{60}\text{Co}$  levels in algae were less than  $0.4 \text{ Bq.kg}^{-1}$  wet in 2008 near the Sellafield plant (CEFAS, 2009).

Concentration levels observed in the North Cotentin, in the area impacted by effluents discharged from the AREVA NC La Hague plant, were less than  $1.5 \text{ Bq.kg}^{-1}$  dry in molluscs (limpets). As observed for the marine environment as a whole, concentration levels have dropped in this area since the 1980s, reflecting the falling quantities of radioactive effluents discharged to the sea. In 1987, concentration levels in mussels ranged from 20 to  $60 \text{ Bq.kg}^{-1}$  dry (Germain *et al.*, 1990). Cobalt-60 levels in the Irish Sea, in the vicinity of the Sellafield plant, were below the detection limit for fish in 2008 and less than  $2 \text{ Bq.kg}^{-1}$  wet for crustaceans and molluscs (CEFAS, 2009).

## Metrology, analytical techniques and detection limits

Owing to the high energy and high emission intensity of its photon radiation (Figure 1), whatever the gamma detector used and the solid, liquid or gaseous matrix considered (AFNOR, 2008; ISO, 2007),  $^{60}\text{Co}$  is, in most cases, easy to measure in environmental samples using gamma spectrometry (Figure 2).

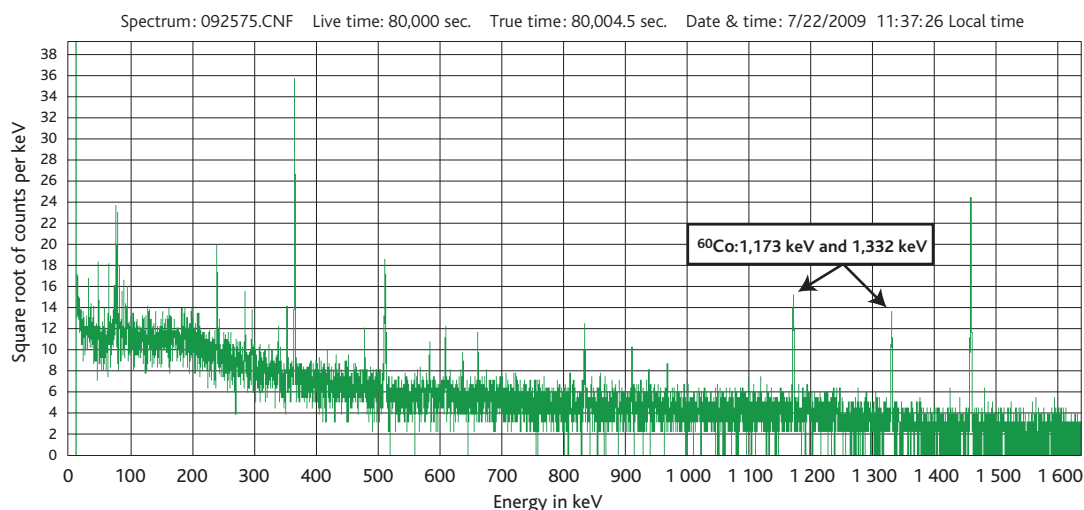


Figure 2: Example of gamma spectrum obtained from an environmental sample containing  $^{60}\text{Co}$ .

For example, measurement laboratories involved in environmental monitoring activities routinely obtain detection limits below  $1 \text{ Bq.L}^{-1}$  or  $\text{kg}$  (sample in 500 mL beaker, n-type coaxial detector, approx. 50% efficiency, 24h measurement). Standard techniques have detection limits in the region of  $200 \text{ mBq.kg}^{-1}$  wet (Renaud, 2010).

During measurements carried out in contact with the detector (which is the most common case), a correction factor may have to be applied to correct for count loss due to the coincidence sum effect (Le Petit and Granier, 2002). This phenomenon occurs when the energy levels of the two gamma rays emitted in cascade by the  $^{60}\text{Co}$  are added together, making it impossible for their individual energy levels to be taken into account in the detection windows. The correction factors to be applied may range from 7 to 10% for a volume of 500 mL in contact with a detector with 50% efficiency. These factors are independent of the count rate.

## Mobility and bioavailability in terrestrial environments

### Soil

Stable cobalt can be found in the soil at concentration levels ranging from 1 to 50 mg.kg<sup>-1</sup> dry (Hamilton, 1994). Higher concentrations have been observed locally in highly mineralised areas (up to 5,000 mg.kg<sup>-1</sup> dry) or on soils formed on serpentine (Coughtrey and Thorne, 1983). Concentration levels observed in France range from 2 to 23 mg.kg<sup>-1</sup> dry, with extreme values of up to 150 mg.kg<sup>-1</sup> dry in highly mineralised 'metallotect' areas, particularly in the Morvan (Baize, 2000). Pastureland soils are often lacking in cobalt (< 1 mg.kg<sup>-1</sup> dry), in which case supplements of this trace element are required to ensure proper nutrition for livestock (Hamilton, 1994).

Many cobalt speciation and sorption-desorption studies have been carried out in simple media (especially metal oxides) and under conditions applicable to certain deep geological repositories (Brooks *et al.*, 1998; Brooks and Carroll, 2003; Khan *et al.*, 1995; Wang and Papenguth, 2001; Wang *et al.*, 2003). Studies of cobalt's behaviour in soil, however, are more general in scope.

Regarding speciation, cobalt would appear to be found mainly as Co<sup>2+</sup> under pH and redox potential conditions similar to those prevailing in 'average' soils. Cobalt hydroxides seem to predominate for pH values beyond 9.5 and tend to precipitate, while sulphides only appear under reducing conditions (Eh < -300 mV at pH 7) (Krupka and Serne, 2002; Deltombe and Pourbaix, 1966). Cobalt forms highly stable complexes with organic ligands, especially humic and fulvic acids (Glaus *et al.*, 2000), which would enhance its mobility. It is recognized that the chemistry of this element is closely related to that of iron and manganese and that it is closely associated with metal oxy-hydroxides. Its strong affinity for iron oxides enhances its mobility in reducing media, especially when they are hydromorphic. Nonetheless, the control of its mobility is dependent on metal oxy-hydroxides and Ca<sup>2+</sup> concentration, as well as the presence of organic ligands (Bresson *et al.*, 2009; Krupka and Serne, 2002). Cobalt sorption on pure mineral phases is moderate and decreases with the pH in the absence of organic ligands, whereas in the presence of organic complexing agents, sorption decreases through the formation of anionic complexes (Krupka and Serne, 2002; Wang *et al.* 2002).

While cobalt is not highly mobile in soil, this is not the case of its complexed forms, which are readily plant-available. Most of it would appear to be slightly adsorbed on clays, after binding with iron or manganese oxides, or else complexed by humic acids. Only some 5 to 10% of the total cobalt found in soil is water-soluble or readily extractable (Colle *et al.*, 1991; 1996). Sequential extractions from paddy soils have shown a significant change in exchangeable fractions and very strongly bound fractions. The cobalt in these two fractions would appear to diminish within a few months, while cobalt associated with iron oxides increases (Tagami and Uchida, 1998). Besides K<sub>d</sub> values increase with clay content. Thus, Gutierrez and Fuentes (1991) found K<sub>d</sub> values of 151 and 318 L.kg<sup>-1</sup> dry for soils which differed mainly in their clay content, *i.e.* 16 and 31% respectively, based on cobalt concentrations of 1 mg.L<sup>-1</sup> in the soil solution.

Cobalt migration depends on soil characteristics. In terms of pH, mobility decreases parallel with acidity. Leaching is moderate in soils with low cation exchange capacity, such as sandy acid soils. Soils or horizons that are rich in organic matter would appear to bind cobalt more strongly and for longer periods of time. In this case, the fraction that can be remobilised is about 5% per year, with the half-life in the humic layer ranging from two to twelve months (Colle *et al.*, 1991; 1996). Soil structure is also an important factor. Albrecht *et al.* (2003) revealed specific preferential migration phenomena and a higher K<sub>d</sub> value in cobalt measured in a batch system, compared with migration in lysimeters.

### Plants

Cobalt is a trace element that would appear to play a role regarding symbiotic nitrogen-fixing bacteria, so that its excess could lead to a decrease in chlorophylls and iron absorption (Chatterjee and Chatterjee, 2000). Plant absorption of the element is dependent on the concentration of the cobalt mobile in the soil, the cobalt found in exchangeable sites, and its chemical form. Because of the element analogy with nickel, histidine seems to be the carrier for cobalt uptake in plants (Bresson *et al.*, 2009). Most terrestrial plants do not exhibit bioconcentration of cobalt, apart from a few hyperaccumulating plants. Average concentrations in plants vary from 0.1 to 115 mg.kg<sup>-1</sup> dry. Concentrations 10 to 20 times higher than this have been observed in legumes in hydromorphic soils (Coughtrey and Thorne, 1983). In cobalt-rich soils, natural plant concentrations can reach values of 100 to 1,000 mg.kg<sup>-1</sup> dry, particularly in the *Nyssa sylvatica* tree (Chatterjee and Chatterjee, 2003).

Average root transfer factors are around 0.1 kg.kg<sup>-1</sup> (dry weight) and vary between 10<sup>-4</sup> and 5. On average, values can vary in a particular plant by a factor of 10, although variability can be far greater than this between different plant species and according to the type of soil.

As for most cations, root absorption is believed to slightly increase with the decrease in pH, as shown in the results of Gerzabek *et al.* (1994). Conversely, the results obtained by Ban-nai and Muramatsu (2002) on radishes grown in ten moderately acid soils (pH from 5.5 to 6.5), and those obtained by Gerzabek *et al.* (1998), do not reveal any significant variation in root transfer with soil pH. Iron, aluminium and calcium have an impact on cobalt absorption by plants through competition for soil exchange sites (exchange capacity). The texture of the soil and its organic matter content modify the intensity of root transfer (Colle *et al.*; 1996; IAEA, 2010), albeit to a lesser degree. Uptake in dicotyledons is higher than in monocotyledons - by a factor of 15 on average. The impact of a stable cobalt contribution to the soil was measured by Colle *et al.* (1991) during their tests, using large lysimeters (16 tanks x 200 kg of brown limestone). The tests conclude that the addition of stable cobalt to the soil increases the root transfer factor. For an amendment of 50 g of stable cobalt per kg of dry soil, <sup>60</sup>Co transfer is multiplied by about 8 for cereal straw and bean pods, by 4 for cereal grain and by 2 for vegetable leaves (salad vegetables, beans, carrots). Deposition on the soil surface also increases transfer compared with uniform uptake in the root layer (Colle *et al.*, 1983; 1996).

Studies on the impact of uptake mode show that overall deposition on the aboveground parts of the plant (spraying on leaves) is by far the most conservative as it increases transfer factors (expressed in Bq.kg<sup>-1</sup> of plant per Bq.m<sup>-2</sup> of cultivated soil) by a factor of 10<sup>2</sup> to 10<sup>3</sup> compared with root uptake of the same equivalent surface activity (Colle *et al.*, 1991). These results are consistent with those of Sabbarese *et al.*, (2002), who compared the specific activity of tomatoes grown using spray irrigation and corrugation irrigation methods: the ratio is about 6.5 for the fruit, 6.2 for the stems, 5.3 for the leaves and 2 for the roots.

The few available results concerning occasional foliar contamination vary furthermore considerably with the vegetative stage at the time of contamination. Regarding experiments on cereals that were spray-contaminated at various vegetative stages, Coughtrey and Thorne (1983) reported the classical observation that the initial percentage of radionuclide retained by the plant at the time of contamination depends on the biomass at the stage in question, whereas the percentage retained by the plant at harvest time depends on the interval between harvest and contamination. Grain contamination reaches its peak when contamination occurs during the maturation period, then drops, while straw contamination increases as the contamination date approaches the time of harvest. This means that translocation to the grain occurs over a short period of time.

## Animals

The average concentration of stable cobalt in animals is in the region of 0.02 mg.kg<sup>-1</sup> wet. It appears that 10 to 100 times more cobalt is transferred to animal products when the cobalt is incorporated in organic rather than inorganic form (Coughtrey and Thorne, 1983).

Very few studies mention transfer factors to animal products. The mean values adopted by the IAEA (2010) are relatively close to the default values adopted by the NRPB (Green and Woodman, 2003). This has very little importance, however, as cobalt is only found sporadically – if at all – in the terrestrial environment. In addition, concentration factors for meat and milk are relatively low, standing at no more than 0.4 and 0.008 respectively, based on wet weight (IAEA 2010).

## Processed foods

As with other radionuclides, cobalt concentrations found in foodstuffs depend on how crops are processed. Food processing significantly reduces the radioactivity of foodstuffs, with residual activity levels in foods in the region of 50% (Roussel-Debet and Réal, 1995; Colle and Roussel-Debet, 1994).

# Mobility and bioavailability in continental aquatic environments

## Water

In natural water, the cobaltous ion (Co<sup>2+</sup>) and its soluble complexes are the principal dissolved forms. The mobility of cobalt is limited by significant sorption and precipitation processes and conditioned by the affinity of this element for suspended matter and sediments. Bioavailability depends on Ca<sup>2+</sup> ion concentration and on dissolved organic matter. The exchangeable fraction of cobalt in continental aquatic ecosystems is small. This element is frequently associated with manganese dioxide. Its solubility can,

however, increase in media tending to acid (low) pH values or in the presence of organic ligands (ATSDR, 2004) which form neutral or negatively-charged complexes with cobalt.

The average concentration level of  $^{59}\text{Co}$  found in fresh water is  $1 \mu\text{g}\cdot\text{L}^{-1}$  (ATSDR, 2004), although concentrations in excess of  $1,000 \mu\text{g}\cdot\text{L}^{-1}$  have been measured in very localised spots in waterways in farming or mining areas. Between 1990 and 2003, the theoretical average concentration of  $^{60}\text{Co}$  in major French waterways was estimated between  $0.02$  and  $1 \text{ mBq}\cdot\text{L}^{-1}$  (Eyrolle, 2009).

## Sediment

The average concentration level of cobalt in sediment is less than  $20 \mu\text{g}\cdot\text{g}^{-1}$  dry weight (CICAD, 2006). The average specific activity of  $^{60}\text{Co}$  in continental aquatic sediments is in the region of  $1 \text{ Bq}\cdot\text{kg}^{-1}$  dry weight (Eyrolle *et al.*, 2008).

Cobalt distribution in the abiotic compartments of continental aquatic systems is characterised by the strong affinity of the element for sediment. In the case of the water column, suspended matter accounts for 90% of total raw water contamination due to cobalt, with no more than 10% of the metal remaining in solution (Albrecht, 2003).

Cobalt is associated with sedimentary particles and therefore actively extracted from the water column. Cobalt sorption-desorption on matter occurs in two consecutive phases, one fast, reversible phase characterised by a  $K_d$ , the other, an irreversible phase caused by the metal binding to sites where steric access is difficult (Ciffroy *et al.*, 2001). The irreversibly-bound fraction increases with the time the particles (suspension and sediment) remain in contact with the cobalt (Bunker *et al.*, 2000). Only 10% of the bound quantity can be exchanged. The type of sediment plays a key role in cobalt retention, especially the levels of iron and manganese oxides and organic matter (Bunker *et al.*, 2000). Adsorption is highest on fine sediment ( $< 0.1 \text{ mm}$ ). The principal binding processes on fine sediment ( $< 4 \mu\text{m}$ ) appear to be, in ascending order: ion exchange, co-precipitation and adsorption with manganese oxy-hydroxides, then carbonates, adsorption on the mineral matrix and, lastly, bonds with iron oxides and hydroxides and with organic matter and sulphides (Borovec, 2000).

The complexation constants of cobalt involving organic ligands found in water, such as tartaric acid, aspartic acid and L-Cysteine have been studied (Jensen and Jensen, 1988). Cobalt complexation by humic acids reveals a slight dependence on pH interaction constants, ionic strength and metal concentration (Hummel *et al.*, 2000). In the  $4\text{-}63 \mu\text{m}$  grain size distribution fraction, the predominant processes are binding to carbonates (22%) and the mineral matrix (32%). Laboratory studies have shown that  $^{60}\text{Co}$  binds mostly (45%) to particles larger than  $450 \text{ nm}$  containing manganese dioxides and iron hydroxides, then to the dissolved fraction ( $< 2 \text{ nm}$ ; 30%) and lastly to colloids (25%) (IAEA, 2009). The wide range of  $K_d$  values reported in the literature (Albrecht, 2003) would therefore seem to be explained by the considerable variability in the density of sorption sites and in suspended particles concentration. Although many authors postulate that cobalt has a strong tendency to sorption, *in situ* observations tend to indicate that this inclination is far less pronounced, as the particle load is generally much lower than that observed in the laboratory (Albrecht, 2003).

The pH is one of the key factors in sorption-desorption processes owing to the fact that cobalt can be hydrolysed. The intensity of cobalt fixation increases in the presence of biological activity (especially oxidation processes governed by microorganisms). This can be explained not only by cobalt accumulation by living organisms, but also by its sorption on carbonate precipitates induced by the photosynthetic activity of phytoplankton (Fournier-Bidoz and Garnier-Laplace, 1994). All these characteristics explain the seasonal variation in cobalt exchange parameters with solid and, more particularly, organic matter (Ciffroy *et al.*, 2001; IAEA, 2010).

## Plants

Transfers to plants are governed by an active process. Cobalt biosorption is controlled by the ion exchange mechanism in algae, while metabolic processes are involved in fungi. Its accumulation by plants is amplified by light. The average concentration level of cobalt in aquatic plants is  $0.1 \mu\text{g}\cdot\text{g}^{-1}$  wet weight (Adam, 1997). The concentration factor varies widely in plants. Values ranging from 2,300 to 40,000 in dry weight have been given for single-cell algae (ATSDR, 2004). More generally, wet weight values range from 20 to 2,800 (Coughtrey and Thorne, 1983; Beaugelin-Seiller *et al.*, 1995; Adam, 1997).

The average specific activity of  $^{60}\text{Co}$  in continental aquatic plants is in the region of  $1 \text{ Bq}\cdot\text{kg}^{-1}$  dry weight (Eyrolle *et al.*, 2008). Single-cell algae are characterised by a concentration factor ( $\text{Bq}\cdot\text{kg}^{-1}$  dry/ $\text{Bq}\cdot\text{L}^{-1}$  water) of 18,000 for  $^{60}\text{Co}$  (Corrisco and Carreiro, 1999). Wet-weight concentration factors of this radionuclide vary from 700 and 1,750 for other plants (Adam, 1997).



## Animals

Cobalt does not generally accumulate in fresh water organisms to a significant extent. Its average concentration level in crustaceans, molluscs and fish is in the region of  $0.1 \mu\text{g}\cdot\text{g}^{-1}$  wet weight (Adam, 1997). Cobalt is found chiefly in the shell and digestive gland of crustaceans contaminated *via* water. The shell accounts for more than 95% of the total contamination in molluscs and very little cobalt is found in the edible part. In fish, cobalt is found mostly in the external organs (skin, gills) and the liver and kidneys, while muscle is the least contaminated tissue. Cobalt-60 has never been reported, however, in the flesh of fish from French continental aquatic systems. Furthermore, the higher up the food chain the organism is, the lower the concentration factor observed. A concentration factor of 15 has been measured in freshwater mussels (Nolan and Dahlgaard, 1991). It varies from 265 for small crustaceans to 2 for trout muscle (Adam, 1997; Fraysse *et al.*, 2002). In the case of freshwater fish, however, it ranges from 10 to 1,000 (ATSDR, 2004). The presence of other metals can interfere with cobalt accumulation by aquatic animals. The presence of zinc, for example, lowers the  $^{57}\text{Co}$  concentration factor in a mollusc by 40% (Fraysse *et al.*, 2002).

Cobalt-60 concentration factors of 2 to 2,000 (expressed in  $\text{Bq}\cdot\text{kg}^{-1}$  wet weight/ $\text{Bq}\cdot\text{L}^{-1}$  water) have been measured in animals (Adam *et al.*, 2001). Very little  $^{60}\text{Co}$  is transferred through food. Trophic transfer factors at equilibrium range from 0.01 to 0.2 (wet weight) for various levels of a pelagic food chain (Adam, 1997; Adam *et al.*, 2001).

## Mobility and bioavailability in marine environments

### Water

Soluble cobalt occurs in seawater in the ionic forms  $\text{Co}^{2+}$  and  $\text{CoCl}^+$  and in the neutral forms  $\text{CoCO}_3$  and  $\text{CoSO}_4$ , the proportions being 54%, 31%, 7% and 7% respectively. Thus 85% of cobalt found in seawater is in cationic form. The cationic forms of cobalt, however, react with the organic acids occurring in the environment to form anionic or neutral complexes (Gaudaire, 1999).

### Sediment

Cobalt concentration levels in sedimentary particles transported to the ocean by water and wind are comparable to those observed in the Earth's crust, *i.e.* around  $20 \mu\text{g}\cdot\text{g}^{-1}$  (Turekian and Wedepohl, 1961). Various processes, such as adsorption and co-precipitation, or sources within the ocean, such as hydrothermalism, cause a significant increase in cobalt concentration associated with various particle phases:  $74 \mu\text{g}\cdot\text{g}^{-1}$  in pelagic clays (Li, 1991), from 100 to  $400 \mu\text{g}\cdot\text{g}^{-1}$  in hydrothermal sediment (Plank and Langmuir, 1998), and up to  $2,700 \mu\text{g}\cdot\text{g}^{-1}$  in polymetallic nodules (Li, 1991). In regions concerned by anthropic contributions, cobalt is associated with sedimentary particles and therefore actively extracted from the water column. As with many metals, the concentration levels of cobalt that binds to sediment depends on the specific surface area of the particles and, therefore, on their size, and mineralogical composition. Values can vary considerable within the same site.

The greater the distance from the outfall pipe, the lower the concentration levels are. Traces are significantly higher in areas of fine sediment, such as estuaries and bays. Advantage was taken of this phenomenon to estimate sediment displacement rates in the Channel (Boust *et al.*, 1997), which were found to range from a few kilometres to several tens of kilometres per year.

Cobalt has a strong affinity for iron and manganese oxy-hydroxides (Jenne, 1968; Murray, 1975). It is associated with iron sulphides in anoxic sediment (Maes *et al.*, 2003). Its reactivity during sediment diagenesis has long been recognised (Heggie and Lewis, 1983; Heggie *et al.*, 1983), although its mobility is considered limited after burial (Gendron *et al.*, 1986). It can be emitted in the water column in the event of massive suspension of anoxic sediment. Martino *et al.* (2002) observed dissolved cobalt concentration levels in the region of 2 to  $4 \mu\text{g}\cdot\text{L}^{-1}$  in the zone of maximum turbidity of the Mersey estuary.

The water-sediment partition coefficients ( $K_d$ , expressed in  $\text{L}\cdot\text{kg}^{-1}$  dry) proposed by the IAEA are  $3 \times 10^5$  for ocean margins and  $5 \times 10^7$  for the ocean floor (IAEA, 2004). In their summary studies, the North-Cotentin Radioecology Group (GRNC, 1999) recommend a value of  $4 \times 10^4 \text{L}\cdot\text{kg}^{-1}$  dry for coastal sediment. The  $K_d$  value proposed by the GRNC was based on *in situ* measurements, taking into account sedimentary storage which incorporates cobalt discharged in previous years. The impact of past releases is corrected for the radionuclide's radioactive decay and makes allowance for a period of sedimentary incorporation (GRNC, 1999).

## Plants

Studies of  $^{60}\text{Co}$  in marine plants were carried out in an area impacted by effluent discharged from AREVA's La Hague spent fuel reprocessing plant. Between 2005 and 2009, concentration levels in the North Cotentin area were found to be around  $3 \text{ Bq}\cdot\text{kg}^{-1}$  dry in the brown alga *Fucus serratus*, an indicator species commonly used in a radioecology and monitoring context. Concentration levels in this area have fallen over time, a phenomenon that is related to the gradual drop in the quantities of effluent discharged to the sea since the 1980s.

Activity ratios between alga samples taken from this area and those taken in the Dover Strait range from 6 to 13 (Germain *et al.*, 1990). These values are higher than those found in chiefly soluble elements such as  $^{125}\text{Sb}$ ,  $^{137}\text{Cs}$ ,  $^{99}\text{Tc}$  and  $^{90}\text{Sr}$ , which illustrates the impact of the element's physical-chemical form on its spatial distribution in marine species.

Concentration factors of 6,000 (in  $\text{L}\cdot\text{kg}^{-1}$  wet) are recommended by the GRNC (1999) and the IAEA (2004) for algae.

## Animals

Cobalt is an essential biological element; it has catalytic functions, activates many enzymes and goes into the formation of metalloproteins. It can be toxic for some organisms.

The GRNC (1999) proposes concentration factors of 5,000 for crustaceans, 2,000 for molluscs and 200 for fish. The values recommended by the IAEA (2004) are 700 for fish, 7,000 for crustaceans, 20,000 for molluscs (except cephalopods) and 300 for cephalopods.

## Mobility and bioavailability in semi-natural ecosystems

This section is based on an international review of the literature as part of the revision of the guide relating to parameter values for predicting radionuclide transfer in temperate continental terrestrial and aquatic environments undertaken at the initiative of the IAEA (IAEA, 2010).

### Forests

There is no specific information on the mobility and bioavailability of cobalt in forest ecosystems.

### Arctic ecosystems

There is no specific information on the mobility and bioavailability of cobalt in arctic ecosystems.

### Alpine ecosystems

There is no specific information on the mobility and bioavailability of cobalt in alpine ecosystems.

## Environmental dosimetry

The effects of exposure to ionising radiation are characterised by the quantity of energy absorbed by the target organism, expressed as a dose rate ( $\mu\text{Gy}\cdot\text{h}^{-1}$ ). Assessment is obtained by applying dose conversion coefficients (DCC,  $\mu\text{Gy}\cdot\text{h}^{-1}$  per  $\text{Bq}\cdot\text{unit}^{-1}$  weight or volume) to concentrations of the radionuclide in exposure environments and organisms ( $\text{Bq}\cdot\text{unit}^{-1}$  weight or volume).

Characteristic DCCs for  $^{60}\text{Co}$  were determined without considering decay products and without weighting the type of radiation (RBE<sup>(1)</sup> not taken into account) using Eden software V2.3 (Beaugelin-Seiller *et al.*, 2006), taking into account shape, dimension and chemical composition of the organisms and their environments, as well as their geometrical relations. Model species considered were chosen as examples.

Internal exposure is characterised by DCCs that vary according to the organism, within a range of  $10^{-6}$  to  $10^{-3} \mu\text{Gy}\cdot\text{h}^{-1}$  per  $\text{Bq}\cdot\text{kg}^{-1}$ .

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<sup>1</sup> Relative Biological Effectiveness: relative efficiency of various types of radiation to produce the same biological effect. This concept may be applied via the use of a radiological weighting factor  $W_r$

For external exposure, most DCCs are in the order of  $10^{-4}$   $\mu\text{Gy}\cdot\text{h}^{-1}$  per  $\text{Bq}\cdot\text{unity}^{-1}$  of weight or volume, although some have values that are two orders of magnitude lower than this.

For more details on how to calculate DCC, see the Environmental Dosimetry Sheet.

## Environmental toxicity

### Chemotoxicity

Cobalt is an essential microelement. It can prove toxic for living organisms when concentration levels are too high. Ecotoxicity knowledge regarding cobalt is such that several environmental protection criteria were defined by various organisations with regard to this element.

In France, for example, INERIS (2006) recommends a  $\text{PNEC}_{\text{soil}}$  (Predicted No Effect Concentration) of  $2.4 \text{ mg}\cdot\text{kg}^{-1}$  dry for terrestrial ecosystems, based on toxicity measurements in earthworms (No Observed Effect Concentration after 24 weeks -  $\text{NOEC}_{24 \text{ weeks}}$  - of  $240 \text{ mg}\cdot\text{kg}^{-1}$  dry, applying an extrapolation factor of 100), whereas INRA proposes an 'investigation threshold' of  $30 \text{ mg}\cdot\text{kg}^{-1}$  dry (Baize, 2000). The US Environmental Protection Agency (2005) has defined guide values (*i.e.* cobalt concentration levels in soils protecting target organisms) ranging from 120 to  $1,300 \text{ mg}\cdot\text{kg}^{-1}$  dry for birds and from 230 to  $2,100 \text{ mg}\cdot\text{kg}^{-1}$  dry for mammals.

For the continental aquatic environment, INERIS (2006) has determined a  $\text{PNEC}$  of  $0.5 \mu\text{g}\cdot\text{L}^{-1}$  (extrapolation factor of 10 applied to whichever is the lowest of alga, fish and invertebrate  $\text{NOECs}$ ). CICAD (2006) has defined a guide value of  $8 \mu\text{g}\cdot\text{L}^{-1}$  in freshwater environments.

INERIS (2006) has gathered chronic data for two trophic levels (crustaceans and fish) in the marine environment, in addition to chronic data available for three trophic levels of freshwater species. With an uncertainty factor of 50 applied to the lowest of the  $\text{NOEC}$  values, the INERIS seawater  $\text{PNEC}$  is  $0.1 \mu\text{g}\cdot\text{L}^{-1}$ .

### Radiotoxicity of the radioactive isotope $^{60}\text{Co}$

The radiotoxicity of cobalt-60 is, for the most part, related to its very high-energy gamma emission. Its effects, however, cannot be distinguished from those of similar emitters. Based on knowledge of the effects of chronic exposure to external gamma radiation, a threshold of  $10 \mu\text{Gy}\cdot\text{h}^{-1}$  has therefore been recommended at the European level. This value is considered as protecting 95% of the species of an ecosystem (ERICA, 2007; PROTECT, 2008).

## Summary

Cobalt-60 is a man-made activation product that normally occurs (with the shorter-lived isotopes  $^{57}\text{Co}$  and  $^{58}\text{Co}$ ) in liquid effluent discharged from nuclear power and waste reprocessing plants. Its naturally-occurring stable isotope,  $^{59}\text{Co}$ , plays a role in leguminous plant nitrogen nutrition and is a vital trace element for animals.

As is the case for stable cobalt, current knowledge concerning the behaviour of radiocobalts in the biosphere remains general in scope, unlike the more mechanistic studies relating to the geosphere. The mobility and transferability of cobalt in the continental environment is average. Its behaviour in the soil is intimately related to metal oxy-hydroxides and, above all, to iron and manganese compounds. Its mobility increases somewhat in acid soils, while it can be significantly immobilised in organic soils. Transfer to plants is average and classically varies with soil and plant type and uptake mode. The main radioecological parameters of cobalt-60 in the soil  $\rightarrow$  plant  $\rightarrow$  food system appear to be relatively complete in operational terms.

In continental aquatic ecosystems, cobalt mobility is conditioned by the element's strong affinity for suspended matter and sediment, which have been the focus of considerable research work. It behaves in much the same way in these compartments as in soil. The exchangeable fraction of this metal is therefore very small in these environments and its transfer is consequently limited in food chains, most levels of which have been studied, with the exception of the higher plants. The higher up the food chain an organism is, the lower the cobalt concentration factors are, falling to values in the region of one for the upper links (predatory fish).

In the marine environment, cobalt chiefly occurs in cationic form in seawater. It is associated with sedimentary particles and is therefore actively extracted from the water column. Its reactivity during sediment diagenesis is well-known, but its mobility is generally considered to be low after burial. It has a strong affinity for iron and manganese oxy-hydroxides. Cobalt-60 levels have dropped significantly in the various environmental matrices since the 1990s, a phenomenon that is related to the gradual decline in the quantities of effluents discharged to the sea. In 2008, it was one of the few anthropogenic, gamma-emitting radionuclides that could be detected in the Channel. It displays a quite considerable binding capacity in marine species. Values vary with the plant and animal group considered, with concentration factors ranging from 200 to 20,000 based on wet weight.

Although cobalt is an essential trace element, it is toxic when concentration levels are too high. Protection criteria based on cobalt ecotoxicity data have been defined for the terrestrial and aquatic ecosystems. Its radiotoxicity is also known for these environments.

## Common radioecological parameters: terrestrial environment

Water-soil distribution coefficient  $K_d$  ( $\text{Bq.kg}^{-1}$  of dry soil per  $\text{Bq.L}^{-1}$  of water)

All	$4.8 \times 10^2$
Sandy and/or silty	$6.4 \times 10^2$
Clayey	$3.8 \times 10^3$
Organic (>30% organic matter)	$8.7 \times 10^1$
pH cofactor:	
pH<5	$1.2 \times 10^1$
5<pH<6.5	$1.9 \times 10^3$
pH>6.5	$4.6 \times 10^3$

(IAEA, 2010)

Foliar transfer factor ( $\text{Bq.kg}^{-1}$  of dry plant per  $\text{Bq.m}^{-2}$ )

Cereals	$1.1 \times 10^{-2}$
Root vegetables (carrot)	$1.8 \times 10^{-1}$

(Colle *et al.*, 1996)

Root transfer factor ( $\text{Bq.kg}^{-1}$  of dry plant per  $\text{Bq.kg}^{-1}$  of dry soil)

<b>Cereals</b>		
Grains	$8.5 \times 10^{-3}$	1
Grains	$7.3 \times 10^{-3}$	2
Stem and aboveground parts	$1.1 \times 10^{-1}$	1
<b>Maize</b>		
Grain	$1.0 \times 10^{-2}$	1
Stem and aboveground parts	$3.5 \times 10^{-2}$	1
<b>Leafy vegetables (leaves)</b>		
Temperate environment*	$1.7 \times 10^{-1}$	1
Tropical environment	$9.2 \times 10^{-2}$	1
Subtropical environment	$1.1 \times 10^{-1}$	1
<b>Leafy vegetables (salad and vegetable foliage)</b>	$5 \times 10^{-2}$	2
<b>Leafy vegetables (roots)</b>		
Subtropical environment	$4.7 \times 10^{-2}$	1
<b>Leafy vegetables (stem and aboveground parts)</b>		
Subtropical environment	$1.1 \times 10^{-2}$	1
<b>Other vegetables (fruit, buds, berries, heads)</b>		
Temperate environment	$1.4 \times 10^{-1}$	1
Tropical environment	$3.1 \times 10^{-1}$	1
Subtropical environment	$7.9 \times 10^{-1}$	1
<b>Legumes (grains and pods)</b>		
Temperate environment	$3.6 \times 10^{-2}$	1
Tropical environment	$6.6 \times 10^{-1}$	1
Subtropical environment	$1.1 \times 10^{-1}$	1
<b>Legumes (stem and aboveground parts)</b>	$6.6 \times 10^{-2}$	1

<b>Root vegetables (roots)</b>		
Temperate environment	$1.1 \times 10^{-1}$	1
Tropical environment	$1.2 \times 10^{-1}$	1
Subtropical environment	$1.3 \times 10^{-3}$	1
<b>Root vegetables (carrot)</b>	$5 \times 10^{-2}$	2
<b>Root vegetables (leaves)</b>		
Temperate environment	$2.4 \times 10^{-1}$	1
Subtropical environment	$1.3 \times 10^{-3}$	1
<b>Tubers (tubers)</b>		
Temperate environment	$5.4 \times 10^{-2}$	1
Tropical environment	$3.7 \times 10^{-1}$	1
<b>Grass (stem and aboveground parts)</b>		
Temperate environment	$7.7 \times 10^{-2}$	1
Subtropical environment	$2.6 \times 10^{-1}$	1
<b>Grassland vegetation (stem and aboveground parts)</b>		
Temperate environment	$4.5 \times 10^{-2}$	1
Subtropical environment	$2.8 \times 10^{-1}$	1
<b>Rice (unspecified environment)</b>	$5.1 \times 10^{-3}$	1
<b>Rice (stable cobalt, unspecified environment)</b>	$6.8 \times 10^{-4}$	1
<b>Fruit tree</b> (fruit: $\text{Bq.kg}^{-1}$ wet weight per $\text{Bq.kg}^{-1}$ of dry soil) (unspecified environment)	$4.8 \times 10^{-3}$	1

\*: if unspecified temperate environment  
 (1)IAEA, 2010 ; 2)Colle *et al.*, 1991)

### Transfer factor for animal products ( $\text{j.kg}^{-1}$ or $\text{j.L}^{-1}$ )

<b>Cow's milk</b>	$6 \times 10^{-5}$ (mineral)	1
	$1 \times 10^{-2}$ (organic)	
	$1 \times 10^{-4}$	2
	$1 \times 10^{-4}$	3
<b>Goat's milk</b>	$5 \times 10^{-3}$	2
<b>Beef</b>	$4 \times 10^{-5}$ (mineral)	1
	$7 \times 10^{-2}$ (organic)	
	$4.3 \times 10^{-4}$	2
	$1 \times 10^{-4}$	3
<b>Mutton</b>	$1.2 \times 10^{-2}$	1
<b>Poultry</b>	$9.7 \times 10^{-1}$	1
<b>Egg</b>	$3.3 \times 10^{-2}$	1

(1) Coughtrey and Thorne, 1983 ; 2) IAEA, 2010 ; 3) Green and Woodman, 2003)

### Food processing transfer factor ( $\text{Bq.kg}^{-1}_{\text{wet}}$ of product processed per $\text{Bq.kg}^{-1}_{\text{wet}}$ of unprocessed product)

<b>Surface water → drinking water</b>	0.4	1
<b>Durum wheat → semolina</b>	0.60	2
<b>Common wheat → flour</b>	0.2	2
<b>Round-grained rice → milled rice</b>	0.60	2
<b>Long-grained rice → milled rice</b>	0.4	2

Vegetables → preserved product	0.3 (0.1 – 0.4)	2
Fruit → preserved product (syrup)	0.6 (0.4 – 0.8)	3
Grape → rosé wine	0.50	3
Grape (bunches) → red wine	0.3	3

(<sup>1</sup>IAEA, 2010 ; <sup>2</sup>Roussel-Debet and Réal, 1995 ; <sup>3</sup>Colle and Roussel-Debet, 1994)

## Common radioecological parameters: fresh water

Water-suspended matter distribution coefficient  $K_d$  (Bq.kg<sup>-1</sup> of dry solid per Bq.L<sup>-1</sup> of water)

General value	3 x 10 <sup>4</sup>
Oxidising conditions:	5 x 10 <sup>3</sup>
Organic suspended matter (with 50% of organic matter)	1 x 10 <sup>5</sup>
Absorption	4.3 x 10 <sup>4</sup>
Desorption	4.9 x 10 <sup>5</sup>
Values measured <i>in situ</i>	4.4 x 10 <sup>4</sup>

(Fournier-Bidoz and Garnier-Laplace, 1994 ; Albrecht, 2003 ; IAEA, 2010)

### Concentration factor in plants (L.kg<sup>-1</sup> wet weight)

Phytoplankton ( <i>Scenedesmus</i> )	700
Diatom ( <i>Cyclotella</i> )	800
Algae	1,500
Mosses	1,750
Macrophytes	1,100
Floating-leaf macrophytes	350
Emergent macrophytes	160
Higher plants in general	710

(Adam, 1997 ; Beaugelin *et al.*, 1995 ; Coughtrey and Thorne, 1983 ; IAEA, 2009, 2010)

### Concentration factor in animals (L.kg<sup>-1</sup> wet weight)

Invertebrates	9.7-22
Crustaceans: daphnia	265
crayfish	2,000
Molluscs: soft part	690
Bivalves: whole organism	1,100
soft part	200
Fish: whole organism	400
muscle	76
Benthic fish: whole organism	160
muscle	81
Burrowing fish: whole organism	530
muscle	300

Piscivorous fish: whole organism	390
muscle	55
Minnow ( <i>Phoxinus phoxinus</i> )	11
Perch ( <i>Perca flavescens</i> )	18
Pumpkinseed sun fish ( <i>Lepomis gibbosus</i> )	80
Blacknose shiner ( <i>Notropis heterolepis.</i> )	20
Carp ( <i>Cyprinus carpio</i> ): whole organism	9
muscle	4.5
Trout ( <i>Oncorhynchus mikiss</i> ): whole organism	4
muscle	2
Tadpole	9,300
Frog: carcass	2,400
muscle	550
Snake (carcass)	2,600

(Adam, 1997 ; Coughtrey and Thorne, 1983 ; Fraysse *et al.*, 2002 ; IAEA, 2009, 2010)

### Trophic transfer factor (Bq.kg<sup>-1</sup> of fresh predator per Bq.kg<sup>-1</sup> of fresh prey)

Crustaceans: (chlorophycea → daphnia)	0.2
Juvenile fish (daphnia → carp)	0.01
Adult fish (carp → trout)	0.08

(Adam, 1997)

### Animal-sediment concentration factor (Bq.kg<sup>-1</sup> wet weight per Bq.kg<sup>-1</sup> sediment)

Invertebrate (whole organism)	0.031
Fish: entire organism	0.29
muscle	0.2
kidney	0.061

(IAEA, 2010)

## Common radioecological parameters: marine environment

### Water-sediment distribution coefficient K<sub>d</sub> (Bq.kg<sup>-1</sup> of dry solid per Bq.L<sup>-1</sup> of water)

Coastal sediment <sup>1</sup> (with a 5-year integration period)	4 x 10 <sup>4</sup>
Deep ocean sediments <sup>2</sup>	5 x 10 <sup>7</sup>
Marginal marine sediments <sup>2</sup>	3 x 10 <sup>5</sup>

(<sup>1</sup> GRNC, 1999 ; <sup>2</sup> IAEA, 2004)

### Concentration factor (Bq.kg<sup>-1</sup> of wet plant per Bq.L<sup>-1</sup> of water)

Macroalgae <sup>1,2</sup>	6 x 10 <sup>3</sup>
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(<sup>1</sup> IAEA, 2004 ; <sup>2</sup> GRNC, 1999)



Concentration factor (Bq.kg<sup>-1</sup> wet weight of animal per Bq.L<sup>-1</sup> of water)

Crustaceans <sup>1,2</sup>	5 x 10 <sup>3</sup>
Crustaceans <sup>2</sup>	7 x 10 <sup>3</sup>
Molluscs <sup>1</sup>	2 x 10 <sup>3</sup>
Molluscs (excluding cephalopods) <sup>2</sup>	2 x 10 <sup>4</sup>
Molluscs (cephalopods) <sup>2</sup>	3 x 10 <sup>2</sup>
Fish <sup>1</sup>	2 x 10 <sup>2</sup>
Fish <sup>2</sup>	7 x 10 <sup>2</sup>

(<sup>1</sup> GRNC, 1999 ; <sup>2</sup> IAEA, 2004)

Food processing transfer factor (Bq.kg<sup>-1</sup><sub>wet</sub> of product processed per Bq.kg<sup>-1</sup><sub>wet</sub> of unprocessed product)

Algae → satiyagum	0.5
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(IAEA, 2010)

## Radiotoxicological parameters

## Terrestrial environment

## Dose conversion coefficients (DCCs), expressed in wet weight

	Internal DCC	external DCC
Model species	(μGy.h <sup>-1</sup> per Bq.kg <sup>-1</sup> )	(μGy.h <sup>-1</sup> per Bq.kg <sup>-1</sup> of soil)
Earthworm	6.17 x 10 <sup>-5</sup>	6.08 x 10 <sup>-4</sup>
Snail	8.79 x 10 <sup>-5</sup>	2.64 x 10 <sup>-4</sup>
Titmouse	1.27 x 10 <sup>-4</sup>	nd*
Rabbit	2.10 x 10 <sup>-4</sup>	1.96 x 10 <sup>-4</sup>
Fescue	6.88 x 10 <sup>-3</sup>	1.68 x 10 <sup>-4</sup>

\*nd: DCC non determinable due to distance

## Fresh water

## Dose conversion coefficients (DCCs), expressed in wet weight

	Internal DCC	external DCC	
Model species	(μGy.h <sup>-1</sup> per Bq.kg <sup>-1</sup> )	Sediment (μGy.h <sup>-1</sup> per Bq.kg <sup>-1</sup> )	Water (μGy.h <sup>-1</sup> per Bq.L <sup>-1</sup> )
Algae	3.73 x 10 <sup>-6</sup>	1.37 x 10 <sup>-6</sup>	4.33 x 10 <sup>-4</sup>
Daphnia	4.75 x 10 <sup>-5</sup>	5.04 x 10 <sup>-6</sup>	9.92 x 10 <sup>-4</sup>
Chironomidae	4.17 x 10 <sup>-5</sup>	5.42 x 10 <sup>-4</sup>	2.34 x 10 <sup>-4</sup>
Roach	1.34 x 10 <sup>-4</sup>	5.38 x 10 <sup>-6</sup>	9.75 x 10 <sup>-4</sup>
Common carp	3.49 x 10 <sup>-4</sup>	1.89 x 10 <sup>-4</sup>	6.96 x 10 <sup>-4</sup>
Water milfoil	6.50 x 10 <sup>-4</sup>	3.83 x 10 <sup>-4</sup>	1.93 x 10 <sup>-4</sup>

**Ocean water****Dose conversion coefficients (DCCs), expressed in wet weight**

Model species	Internal DCC ( $\mu\text{Gy}\cdot\text{h}^{-1}$ per $\text{Bq}\cdot\text{kg}^{-1}$ )	external DCC	
		Sediment ( $\mu\text{Gy}\cdot\text{h}^{-1}$ per $\text{Bq}\cdot\text{kg}^{-1}$ )	Water ( $\mu\text{Gy}\cdot\text{h}^{-1}$ per $\text{Bq}\cdot\text{L}^{-1}$ )
Phytoplankton	$1.33 \times 10^{-5}$	$2.13 \times 10^{-6}$	$9.79 \times 10^{-4}$
Fucus (tuft)	$4.42 \times 10^{-4}$	$3.89 \times 10^{-5}$	$7.13 \times 10^{-4}$
Zooplankton	$5.63 \times 10^{-5}$	$3.01 \times 10^{-6}$	$9.33 \times 10^{-4}$
Lobster	$2.38 \times 10^{-4}$	$1.97 \times 10^{-4}$	$4.58 \times 10^{-4}$
Plaice	$1.70 \times 10^{-4}$	$3.18 \times 10^{-4}$	$4.79 \times 10^{-4}$
Mackerel	$1.72 \times 10^{-4}$	$3.95 \times 10^{-6}$	$9.21 \times 10^{-4}$

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